# Strategic Building Energy Management, Policies, and Insulation Materials

by

**Mrinal Jha**

**A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Engineering
(Energy Systems Engineering)
in the University of Michigan-Dearborn
2021**

**Master's Thesis Committee:**

**Professor Pankaj K. Mallick
Professor Yubao Chen
Lecturer III Roger Klungle**

## DEDICATION

In loving memory of my Grandfather

## ACKNOWLEDGEMENTS

I acknowledge all the people who have played their part to prevent climate change and those who are actively striving to maintain our planet's integrity. The research performed in this study is a conspicuous effort from my end to honor those noble minds.

I am grateful to my advisor, Dr. P.K.Mallick, who was gracious enough to not only accept my proposal for collaborating with him on an independent research, but also had the confidence in me to develop that proposed independent research into a much more meaningful and impactful thesis. I thank him for the time that he has spent guiding me and nudging me in the right directions whenever I had an iota of doubt. Under his expertise I find myself an improved engineer and more importantly a better person. I can only wonder the influence he would have had over me if I had met him in person rather than just over the internet.

I thank my committee members Dr. Roger Klungle and Dr. Yubao Chen, for their time and enthusiasm to be on the panel as I defend my thesis. This research would not have been possible without the skills and knowledge that I acquired under Dr. Roger Klungle, who taught me to approach problems from a wholistic point of view instead of independent unconnected events. The influence of Dr. Yubao Chen in this thesis is profound with the concepts of Total Quality Management being frequently invoked. Under his auspice I learnt the concept of doing things right the first time, which I then utilized to fine-tune my research and analysis.

I would like to extend my gratitude towards my family and friends, the few people I could meet in person during my study. They have kept me motivated throughout my life and provided meaning to it. It is always a pleasure to interact with them and take a break to revitalize myself amidst all my professional endeavors. I am encouraged to spend time with them as I realize that after every rendezvous, I find a fresh sense of perspective to get around problems and pick up from the point I had left off from with added zeal.

I am also grateful to have the backing of Electrical and Computer Engineering department and especially Mr. Michael Hicks, who has kept me informed of all the formalities to negotiate my way through the research and keep me on track. My special thanks to all the members of the UM-Dearborn E-Challenge team, of which I was a part of and had the honor of winning the inaugural energy efficiency competition in the state of Michigan. This thesis greatly inspired by my stint at the University's energy team learning the nuances of energy industry.

Finally, I would like to thank in advance all the readers who will spare their precious moments going through this thesis. I hope that this work is sound enough to urge them to realize their responsibility to the environment. Ultimately, all of us want to leave behind the gift of life for our future generations as our ancestors did for us, with earth in its pristine form.

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

**LIST OF APPENDICES**

## ABSTRACT

The building sector is responsible for 15% of energy consumption and 40% of greenhouse gas emissions (GHG) in the world. Among the various building energy uses, heating and cooling require 40% of the energy in residential houses and 27% in commercial buildings. To reduce energy use in heating and cooling, it is important that improved insulation be used that will increase the thermal resistance of heat flow from outside in summer months and from inside in winter months. This research focuses on the selection of best insulation materials in buildings from the standpoints of energy saving and greenhouse gas potential using a decision-making process known as Analytical Hierarchal Process (AHP). A modified form of AHP was used to compare various synthetic and natural insulation materials on various attributes based on their thermal, environmental, and cost performance. Out of eleven materials considered, coir, a natural fiber, performs better than fiberglass, the best performing synthetic fiber, and hemp, another natural fiber, performs almost equal to fiberglass.

This thesis also discusses the building energy codes and barriers to building energy transition. The role of strategic building energy management is demonstrated trough a case study which has shown that implementation of energy audit and conservation measures can save both energy and money in the long term.

# CHAPTER 1
# INTRODUCTION

Analyzing the history of energy sector tells us which source of energy has been traditionally used, what purpose they served, how much emissions they released and when were subsequent sources of energy discovered, developed, and used. The pre-modern world used biomass for majority of its energy production. Agriculture was the major economic activity and understandably very labor intensive [1]. Contingent on cattle for ploughing and tilling, the animal stock in turn dependent on agriculture for fodder [2]. Although products of agriculture are renewable sources of energy, they cannot be classified as emission free. Primarily wood, and products of wood (furniture shavings, chips, and pellets) were used for lighting, cooking and even heating households. Biomass like crops, organic wastes, and residue from harvest, such as corn and sugarcane, also addressed energy needs. Many developing and underdeveloped economies still rely on renewable, but carbon emitting source of energy as answers to daily chores. The efficiency of primitive forms of energy was very low compared to the present-day forms of energy that include a variety of sources, such as coal, nuclear, etc.

Data in terms of energy intensity, population, and GDP cannot be determined accurately before the industrial revolutions as proper records were absent [3]. Reliable data of population, GDP and energy sources came only in the $19^{th}$ century with the evolution of modern energy sources like coal and petroleum [1]. Owing to rapid industrialization and use in steam engines for railways and ships, coal became the primary source of energy replacing wood which was less efficient. Other modern sources of energy like natural gas, nuclear power, and renewable energy systems came into the energy fold in the $20^{th}$ century. Modern sources of energy have grown over the years since mid-$19^{th}$ century to over 700 times compared to biomass which only increased 5 times in the same period. The increase in biomass can be understood mainly in terms of rise in population growth rate which started to peak in 1960s but has since shown a downward trend, although absolute population remains increasing.

The use of modern forms of energy has been consumed by industrialization and transport amongst other factors. With industrialization came railways and ships which started transporting goods and passengers contributing to increased GDP and Tons of Oil Equivalent (TOE) per capita. On an average the energy consumed by a person has increased eight times and this has happened along with global population rise of almost 6 times [4]. To understand the demand in energy this will amount to $6^8$ times amount of energy consumed in the 1800s approximately.

Beginning of 20$^{th}$ century saw a gradual shift from coal toward sources with higher energy content like oil. Discovery of oil and invention of internal combustion engine made this commodity the most widely used fuel in the United States in 1950. Discovery of nuclear fission for energy and creation of large hydroelectric projects led the way to alternative sources of energy. Late 1900s saw large scale farms of wind turbines, photovoltaics, and solar thermal power projects, once again the United States leading the way to producing electricity through renewable energy sources [5]. Data after 1980 has been extensively collected throughout the world with respect to sources of energy, demands, consumption and emissions.

**1.1 Status of Energy and Emissions**

The following section shows trends of energy, production, energy consumption and emissions throughout the world and USA. Energy production (in Quad Btu) is defined as amount of energy generated from primary energy sources. According to EIA, some of the sources of primary energy are coal, natural gas, crude oil, nuclear electricity net generation, geothermal energy, wind energy, solar thermal energy, photovoltaic (PV) electricity, biomass waste consumption, and wood derived fuels. Energy consumption (in Quad Btu) is defined as the utilization of primary energy in all its forms. According to EIA, some of the primary energy consumptions are coal consumptions, coal coke net imports, petroleum consumption, nuclear electricity net generation, conventional hydroelectricity net electricity generation, biomass waste consumption, fuel ethanol and biodiesel consumption, electricity net imports and so on [6]. Emissions (in million metric tonnes of $CO_2$) can be defined as unwanted particulate matters and gases that are released to the ambient because of different human activities and natural causes. Some of the leading Greenhouse Gas (GHG) emitters due to human activities are the transportation, electric, cement and steel industries [7].

The data for the energy and emissions trends, given in the Appendix-1 and plotted in Figures 1.1-1.4 were taken from the EIA website for successive years between 1980 and 2017 [8]. The trends start off flat with a slow fall in 1980 owing to an economic recession and so the emissions in Figure 1.3 are also flat during the recession between 1979 and 1984 after which there is a slow growth in energy production. Due to oil embargo of 1973-74, countries which were initially heavily dependent on OECD cartel, started investing in alternate energy sources and reduced their dependencies on petroleum from OECD countries. This meant construction of new energy projects in the form of coal fired power plants, nuclear power plants, renewable energy like wind, solar, hydroelectric, geothermal, ethanol as alternate to gasoline (specially in Brazil). After the recession ended, manufacturing and service industries picked up and contributed to emissions which can be seen between 1984 and 1990. During the next five years, the emission curve is essentially marked by a gradual increasing trend. This can be reasoned by the fact that after a wave of manufacturing and industrial companies lay their foundation, there is a tremendous scope for the service industry to support manufacturing and create jobs. This essentially is followed by a rapid increase in emissions between 1995 and 2007. The key drivers to this trend are China and India. India opened its economy and there were huge investments from around the world to tap into the immense potential of India for different products due to its population. China also started large scale manufacturing and became one of the largest GDPs during the same period.  However, the recession of 2008 hit all the countries extremely hard and there was a rapid decline in energy consumption as well as emissions. As the economies again picked up pace, emission growth rate plummeted in 2010. After the 2015 Paris Agreement [9], there is growing consciousness especially in Europe to tackle uncontrolled GHG emissions and many task forces have been created to tackle climate change.

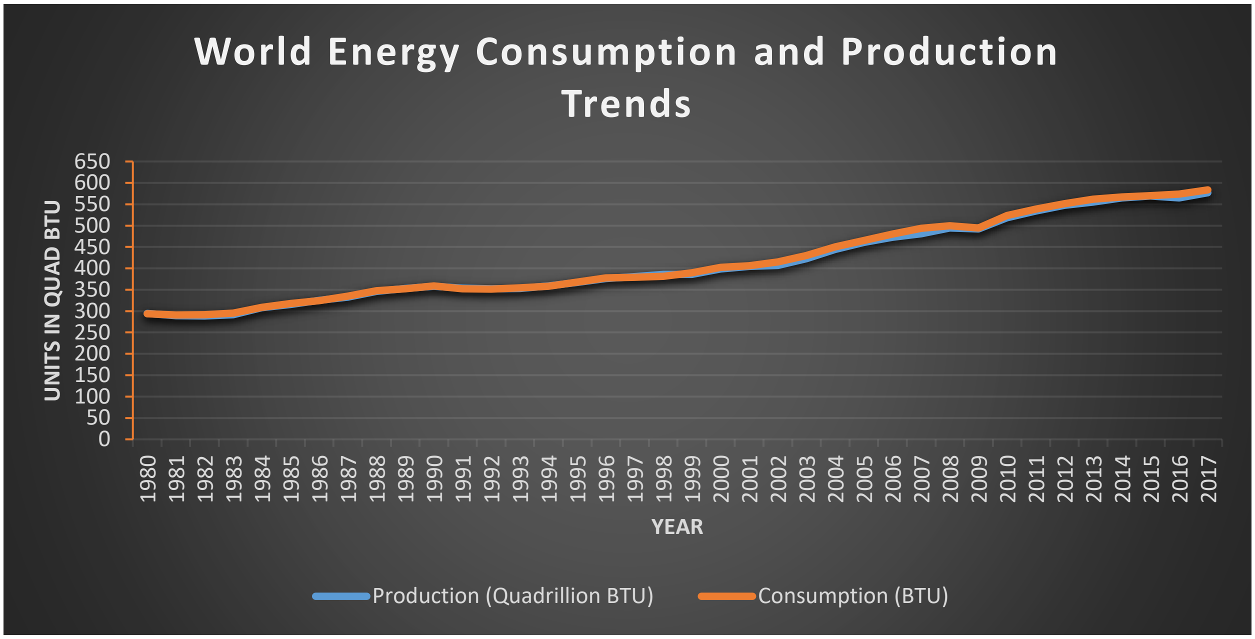


**Figure 1.1:** World energy production and consumption trends (1980-2017).

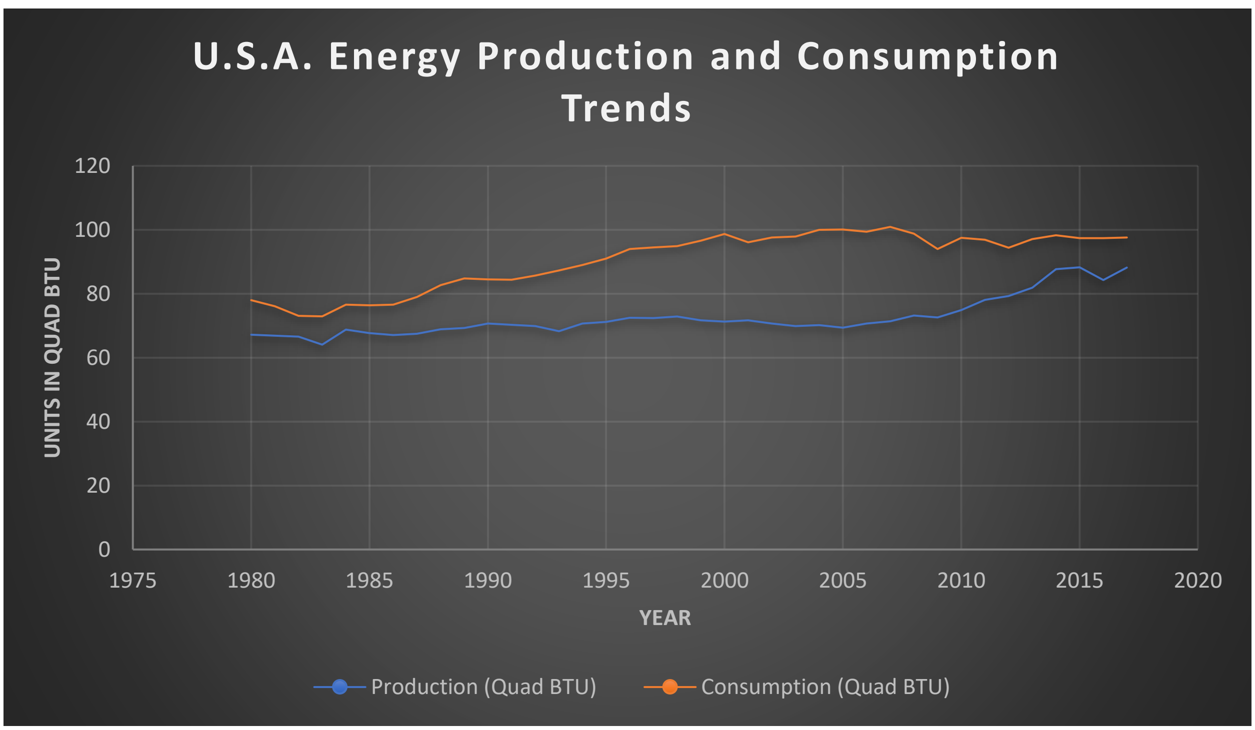


**Figure 1.2:** USA energy production and consumption trends (1980-2017).

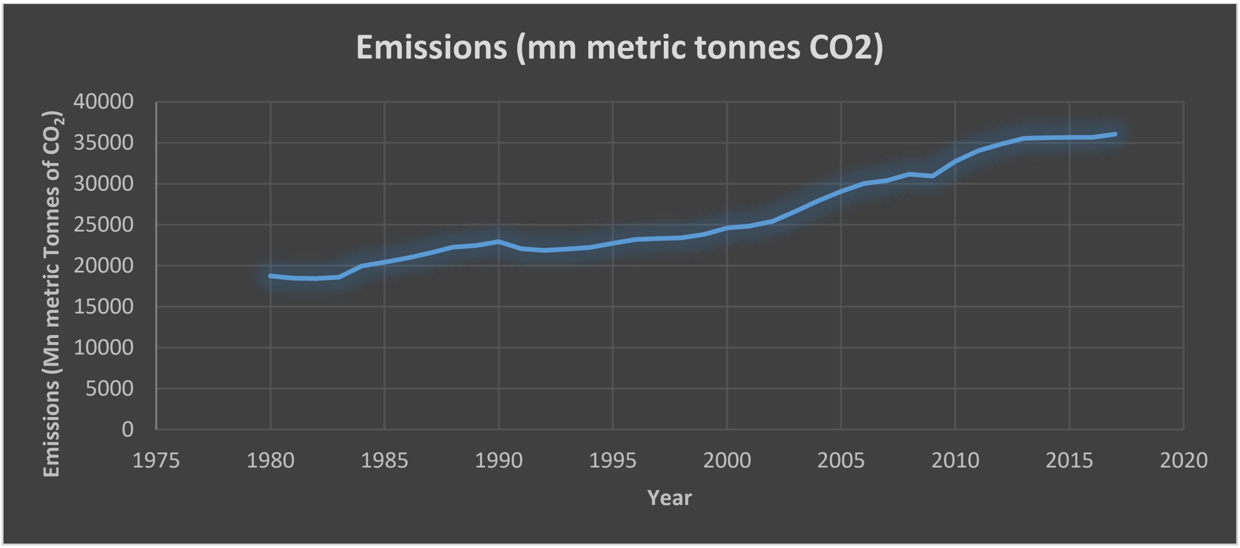


**Figure 1.3:** World emission trends (1980-2017).

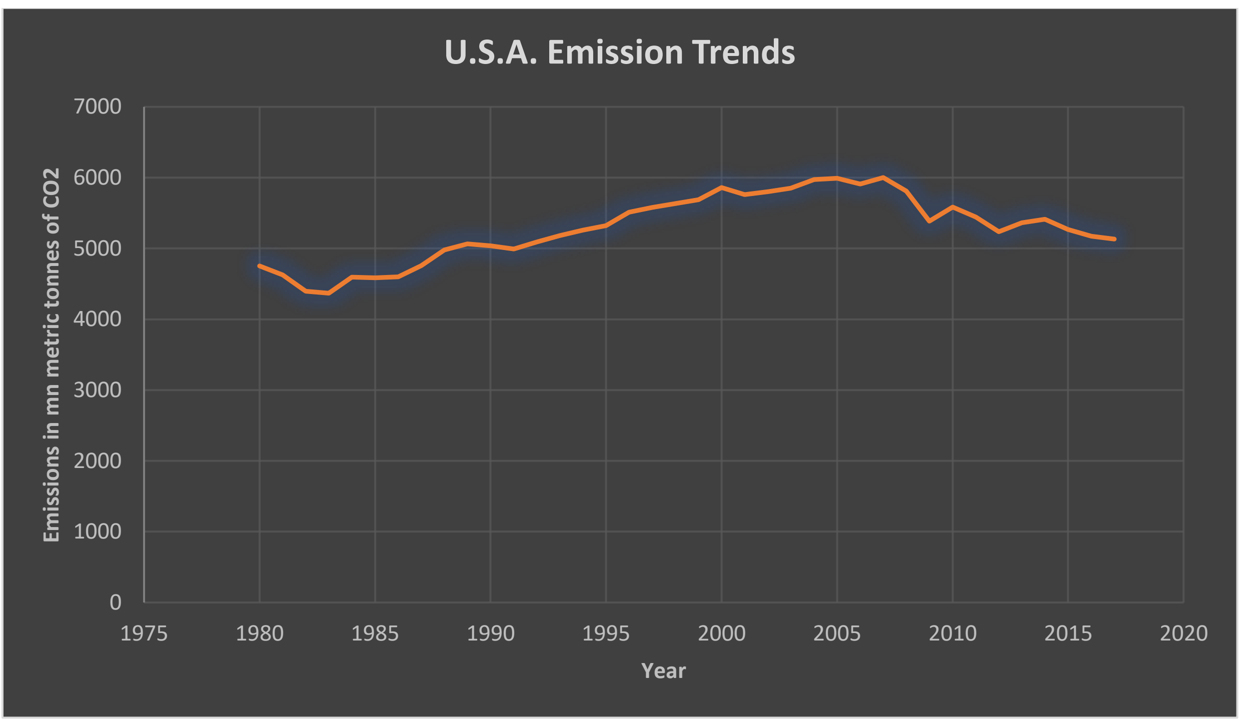


**Figure 1.4:** USA emission trends (1980-2017).

## 1.2 Energy by Sector

Energy consumptions in different sectors of economy is listed in Table 1.1 and are briefly described in this section.

(a) Residential sector

It is comprised of the energy consumed due to various household activities. The amount of energy consumed throughout the world was just under 10% of worldwide energy consumed by all sectors out together. With rise in population, this sector is expected to grow and so will the energy consumption. But there is a ray of hope using efficient lighting and appliance policies, strict building codes, its enforcement, and increased state support in various energy efficiency schemes. In the U.S.A., the energy consumed in this sector through 2030 [11], is expected to be flat since the aforementioned measures are being applied.

**Table 1.1:** Sector-wise energy consumption for year 2020 [10].

| **Sector** | **Energy Consumed (Quad BTU)** |
|---|---|
| Residential | 59.8 |
| Commercial | 33.3 |
| Industrial | 240.1 |
| Transportation | 123.8 |
| Losses related to electricity | 171.7 |
| Total | 628.7 |

(b) Commercial sector

This sector is comprised of various facilities of government, service-providers, public and private organizations [12]. It accounted for over 5% of the total energy consumed in the year 2020. Most of the energy consumed in this sector, like the residential sector, is due to heating, ventilation, and air conditioning (HVAC) and lighting. It occurs during operating business hours and energy consumed is lowest during night-time and weekends. Tremendous energy is saved by lighting retrofits in this sector as they are operated for long durations cutting short the payback period.

(c) Industrial sector

In this sector, energy is consumed by the equipment and facilities of industries which process, produce of assemble goods. Agriculture, mining and construction industries are integral parts of this sector. This sector consumed almost 40% of all energy consumed worldwide in the year 2020. The fluctuations in energy consumed is flat unlike industrial or residential sectors where energy consumed usually peaks in certain times or months of the year [12]. This is because of production of goods and sometimes energy consumed remains the same when production is round the clock. It is difficult to reduce energy consumed in many industries because processes are already optimized but the industries are trying hard to do so, as energy bills is a major capital expense.

(d) Transportation sector

This sector consumes most of the energy from direct combustion of fossil fuels but with the advent of electric vehicles percentage dependence on electric power from the grid could increase. Close to 20% of the total energy worldwide energy is utilized in the transportation sector. This can be brought down if stricter energy policies are enforced on fuel consumption performance of various segments of vehicles. A model example is in the U.S.A., which is the CAFE (Corporate Average Fuel Economy) standards [11]. Electric Vehicles (EVs) can also act as energy storage options for the grid, feeding back power when demand on the grid is high [12].

(e) Losses related to electricity

It is the losses associated with distribution of energy to various sectors [10]. This accounts for more than a quarter of the total energy produced. It is also a number which shows the scope of improvement possible for sustainable development.

### 1.3 Emissions by Sector

Three quarters of emissions are released on our planet through the end use source as energy. With rising population and economic development, the energy sector becomes a key driver to increasing carbon emissions. To reduce emissions, we need to have a clear picture of the sources responsible for it. Table 1.2 reflects the data of various sources.

(a) Buildings (17.5%)

This sector is split into commercial and residential sectors with 6.6% emissions arising from the former and 10.9% from the latter [7]. HVAC systems, water heating, lighting, appliances and cooking are the main reasons of energy use in houses, offices, restaurants, shopping malls, etc. While most of the emissions take place in the operation phase of buildings, considerable amount of energy is expended during the construction and disposal phases. Building construction materials, such as cement, concrete, steel, etc., used in the construction phase, although categorized in the industrial sector, are produced for building sector.

**Table 1.2:** Sector-wise emissions [7].

| Sector | Percentage |
|---|---|
| Buildings | 17.5 |
| Industry | 24.2 |
| Transportation | 16.2 |
| Unallocated fuel combustion | 7.8 |
| Direct industrial processes | 5.2 |
| Waste | 3.2 |
| Agriculture forestry and land use | 18.4 |
| Others | 7.5 |

(b) Industry (24.2%)

There are numerous segments in this sector with iron and steel industry responsible for 7.2% of emissions. Paper and pulp, wood, textile, food, chemical, etc. are other instances in this segment which round up this sector for a total of 24.2% of worldwide emissions [7].

(c) Transportation (16.2%)

This sector is composed of road, aviation, ship, and rail. The share of emission arising from each of them are 11%, 1.9%, 1.7% and 0.4%, respectively. Transportation of commodities like oil, water, steam and even hydrogen require inputs in the form of energy to be transferred from one place to another. This form of transportation is categorized under pipelines and contributes 0.3% of emissions [7].

(d) Agriculture, forestry, and land use (18.4%)

Aggregating from deforestation, crop burning, rice cultivation, and livestock makes up a considerable amount of emissions into our environment [7].

(e) Unallocated fuel combustion (7.8%)

Heat and emission generated from biomass, on-site heating requirements, combined heat and power, nuclear industry and pumped hydro storage forms integral part of this segment [8].

(f) Direct industrial processes (5.2%)

It is comprised of the chemical, petrochemical, and cement industries with emission percentage share of 2.2% and 3% [7].

(g) Waste (3.2%)

The amount of waste generated is at its peak. There are numerous landfills which accommodate this waste and due to anaerobic conditions, there is production and release of methane and nitrous dioxide into the environment. Decomposition of organic matter in riverbeds and swamps also adds to this emission [7].

(h) Others (7.5%)

Flaring of methane during oil and gas exploration, burning of coal for various processes like energy production and coal mining makes up this segment. Miscellaneous activities like fishing and agriculture are also there in this category [7].

## 1.4 Building Energy

The total building lifecycle is composed of three phases, namely construction, operation, and disposal. The second phase, i.e., building operation phase is usually responsible for most of the energy used, typically up to about 80 %. While engineers have become conscious in making buildings energy more efficient, yet there is a dearth of knowledge regarding how to use energy efficiently during the construction and disposal phases. With the current building stock expected to double by 2060 [13], it can be expected that related emissions will also nearly double, posing a major threat to the earth's climate. Thus, there is an urgent need to ascertain amount of energy used during the construction and disposal phases.

### 1.4.1 Building Construction Phase

In the construction phase, there are many indirect energies uses that are not understood. For example, energy used by earthmovers and heavy trucks in the form of gasoline and diesel, to move men and materials. With the help of Table 1.3, we will look at some of these causes of energy use so that it can be accounted for energy use during the construction phase. The data in this table were collected during the construction phase of Jack E. Brown Chemical Engineering block in the Texas A&M University. It is a typical research building on the university campus with 7 stories and 205,000 square footage built over 26 months of construction [3].

The construction phase of buildings is broken down into four phases [3]. The activities in each phase are carefully considered and are common for all modern buildings. This is done to standardize and track the use of energy for similar constructions.

Phase I

Prior to the commencement of construction, the site must be prepared. Depending on the location, extensive leveling, removal of vegetation or rocks maybe required. It is the time when waste management is used to channelize all the unwanted materials via specific mediums. Energy used in this phase is mainly gasoline or diesel for earthmovers and excavators which level the site. Depending on the size of the plot it may take anywhere from a 1 to 3 days for this phase. On an average, three hours are required to clear out one acre of land. Out of all the phases, this phase is the least energy intensive and easy to carry out sustainably.

**Table 1.3:** Breakup of energy consumptions during the construction phase of a university building [3].

| Phase | Activity | Equipment | Source | Duration | Energy Consumed (KWH) | Cost (in $) |
|---|---|---|---|---|---|---|
| 1 | Site Clearing, Levelling, waste disposal | Earthmovers and excavators | Diesel or Natural Gas | 2-5 days | Not available | Not known; 3rd party contract |
| 2 | Foundation activity, Rough out for MEP (Mechanical, Electrical, Plumbing) works, Structural Framing | On-site construction trailers, lighting equipment, diesel generator for miscellaneous activities like cutting, welding, etc., Tower Crane for building structure, Material hoists | Temporary electric poles, Generators | 8 months | 1,040 | 88 |
| 3 | Interior and exterior finishing works, milling jobs and setting up fixtures, Mechanical | Temperature and humidity controls, Trailer, Floor and Milling works | Temporary electric supply | 10 months | 233,720 | 22,204 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | controls testing, Temperature and humidity control | | | | | |
| 4 | Commissioning, temperature and humidity stabilization, Flush out of toxic gases and volatile substances | Temperature and humidity controls, flush out equipment, Electrical fixtures | Electric supply from utility company | 8 months | 1,511,488 | 112,344 |

For waste management of materials in the first phase, development of an action plan is important, and it sets up the ethics of the construction firm. During this phase, the unwanted material is dominantly brown waste composed of dry twigs, shrubs, leaves and soil. It can be used in composting pits to restore flora to the environment. Brown waste have the potential to sustainably return the carbon to carbon cycle [3].

Phase II

Following the preparation of the construction site, the next step is to lay out the foundation and base of the MEP (Mechanical Electrical & Plumbing) works. The structural frame of the building is done in this segment. Temporary structures and electrical works are laid out. Piers are drilled to support perimeter walls. Tower cranes are setup to place steel structures, mason work is carried out, duct work is done, and dry walls are setup. Usually temporary material hoists are used in this step.

The whole phase takes about eight months to complete and temporary electric poles and generators are used to supply the energy needs. Diesel generators are used for miscellaneous activities like cutting, welding, and lighting equipment. On-site construction trailers, tower crane for building structures, and materials hoists are other energy consuming activities for this phase. For our specimen building, 1,955 KWh of energy was expended in this phase [3].

Phase III

With the main structure of the building ready, interior and exterior finishing works, such as fixture setup, milling jobs, mechanical controls testing, temperature control and humidity control, are done in this phase Activities like damp proofing, metallic stairs setup, ceramic tiles fitting, lab works, curtain walls construction, piping and testing of air handler for leakage ~~is are~~ done. Elevator and drywall installation, case work, masonry, electrical works, flooring, security lighting, and interior finishing are also done. There is removal of scaffolds, hoists, and cranes too all of which demand energy.

This phase took ten months and 233,720 KWh of energy for our specimen building. This is the second most expensive phase in terms of energy requirement; thus there is tremendous scope to save costs translating to reduced energy consumption and emission. In this phase a temporary electric supply is setup from a utility company [3].

Phase IV

This is the final and most energy intensive phase during which building commissioning is done just before handing over a fully operational premise to the customer. Process of temperature and humidity stabilization is done. Another important activity which is done is flushing out of toxic and volatile substances from the interior of the building. Fire proofing hang entry doors, millwork, plumbing fixtures, remaining drywall installation, roofing, hardware works, trailers removal and landscaping of the premise take place so that the customer is ready to take possession. Temperature and humidity control, flush out, and electrical equipment are used in this phase amounting to 1,511,488 KWh of electrical energy from the utility company. The final phase of the construction activity takes about another eight months [3].

### 1.4.2 Building Operation Phase

The energy consumption during the build operation phase can be divided into four categories, namely HVAC, lighting and appliance, public service and special. The flow chart in Figure 1.5 shows these four categories and several sub-categories. The highest energy consumption occurs in the HVAC system, followed by IT operations and lighting (Table 1.4 and Figure 1.6). A breakdown of the energy consumptions by various components of the HVAC system is given in Table 1.5 and Figure 1.7. The major energy consumption in the HVAC system is due to the cooling requirement during the summer months and heating requirement during the winter months. Both cooling and heating requirements depend on several factors, such as the size of the building, occupancy level, location of the building, and heat flow from the inside to the outside of the building and vice versa. Among these factors, heat flow can be controlled by the materials used in the construction of the walls, roof and windows.

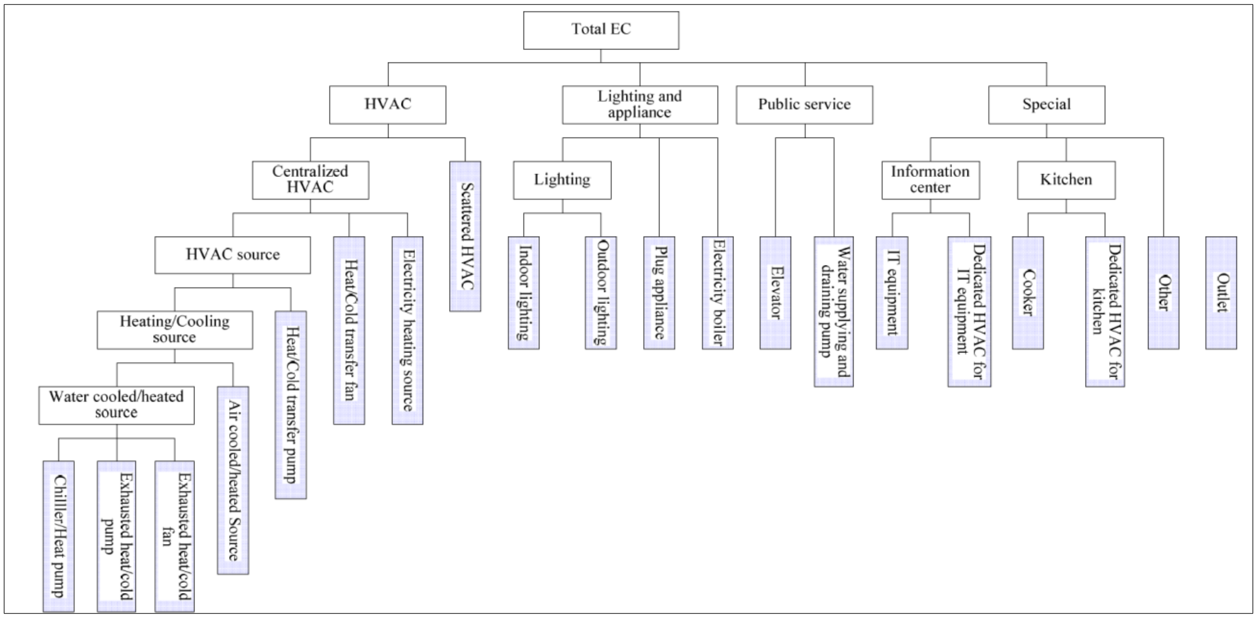


**Figure 1.5:** Electricity consumption flow chart [14].

**Table 1.4:** Energy consumed by subsystems of a commercial building [14].

| Subsystem | Energy Consumed (in %) |
|---|---|
| HVAC | 38 |
| Office Equipment | 29 |
| Lighting | 26 |
| Elevators | 6 |
| Others | 1 |

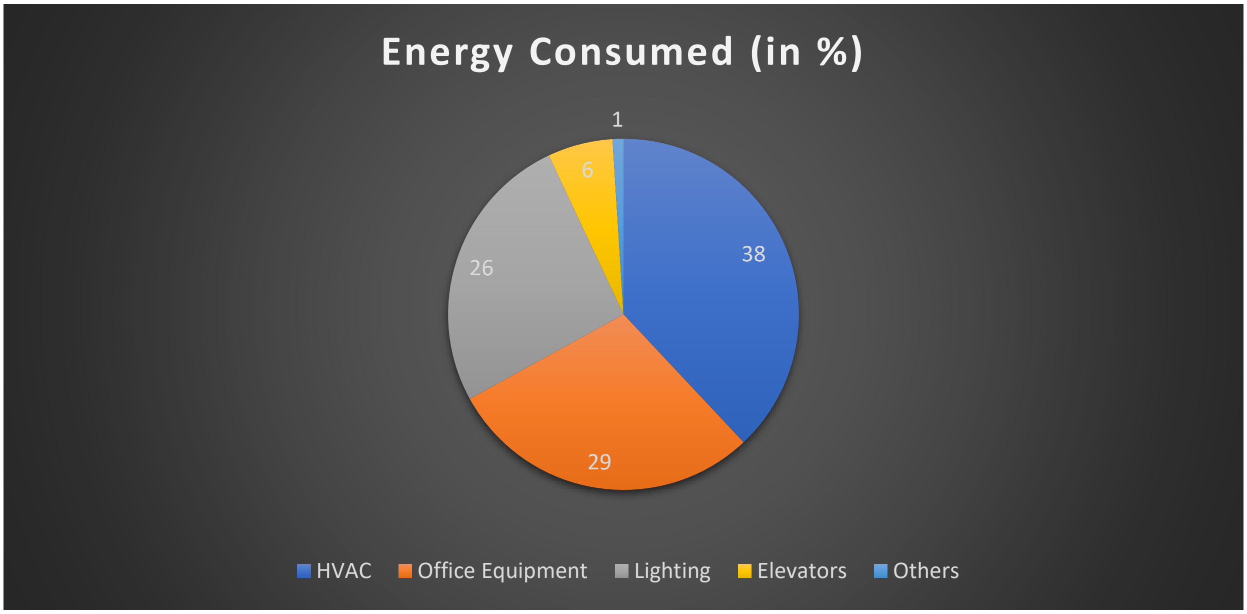


**Figure 1.6:** Energy consumed by subsystems of a commercial building.

**Table 1.5:** Energy consumed by various components of HVAC unit.

| Component | Energy Consumed (in %) |
|---|---|
| Chiller | 18 |
| Air Handling Unit | 13 |
| Cooling Tower Fans | 2 |
| Primary/Secondary Pumps | 2 |
| Condensing water pumps | 3 |

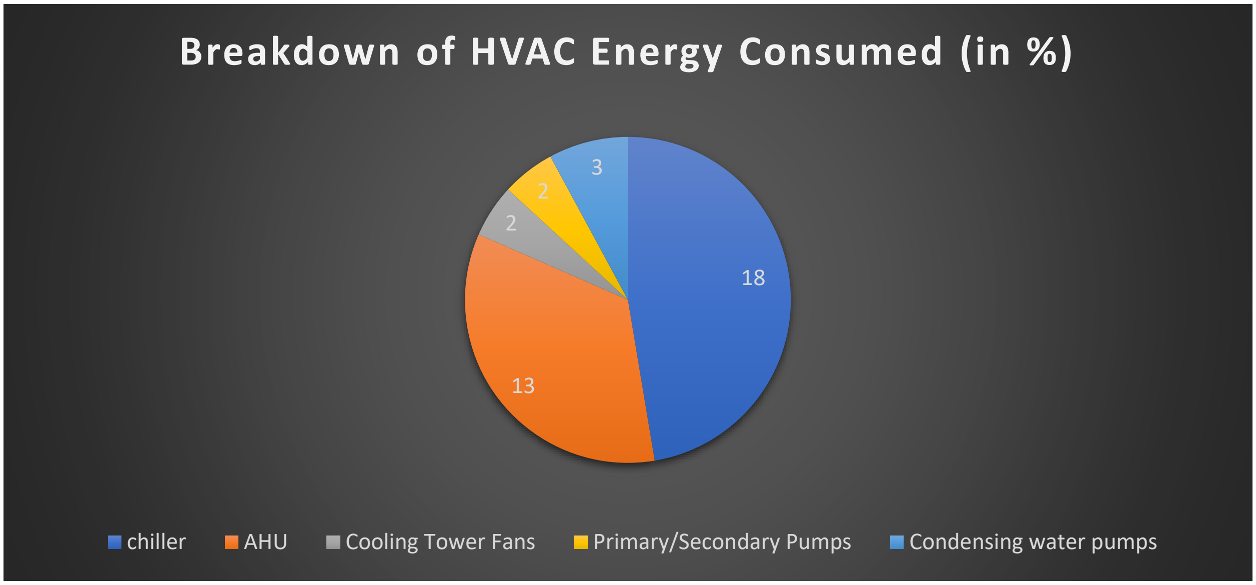


**Figure 1.7:** Energy consumed by various components of HVAC unit.

### 1.5 Objectives

The objectives of this research are as follows.

(1) To understand the building energy policies in the USA and their implementation through building codes

(2) To review building management process and its influence in controlling energy use and reducing emissions from buildings

(3) To investigate the material selection criteria for wall insulation materials in building envelopes and develop a decision-making methodology for making the best selection among a variety of synthetic and natural insulation materials.

### 1.6 Chapter Distribution

Chapter 2, energy policies in the U.S.A. and the different levels of jurisdiction for implementation of energy policies are discussed. This chapter concludes with a high-level discussion on barriers to building energy transition.

Chapter 3 considers the building energy management system and its role in improving energy efficiency and reducing emissions in buildings. A case study involving a UM-Dearborn building is reviewed where the energy teams developed an energy handbook to implement energy conservation measures. It also discusses how an energy audit leads to proposals and how it is beneficial both to the environment and economic savings.

Chapter 4 starts with a discussion on the role of insulation materials in energy savings in a building. Various natural and synthetic insulation materials for an efficient building envelope are evaluated and compared to Fiberglass, one of the leading choices of insulation materials in use today. Building energy levels with different insulation materials are modelled using EnergyPlus software. Then various alternatives for selection of the best insulation material are compared using a modified form of AHP, a decision-making tool.

# CHAPTER 2
# BUILDING ENERGY POLICIES

## 2.1 Building Energy Policy

Energy efficiency and conservation is attained through proper implementation of energy policies and codes. There is a plethora of benefits tied in the bundle of energy efficiency and conservation with improved air quality, low electricity bills, and reduced greenhouse gas emissions to name a few [15].

Despite the obvious advantages, there are plenty of reasons and market conditions which makes adoption of energy efficiency and conservation measures difficult, they are barriers to energy transition. Energy security, environment, and economic development are key policy drivers of energy efficiency recognized by all levels of jurisdiction, yet actions taken by any one level of jurisdiction can jeopardize the plans at another level. For example, a country wants to improve its energy security, so it does not want to depend overtly on any one source of energy source say coal. This pressurizes the policymakers to rely more heavily on a diversified energy portfolio consisting of various renewable energy sources like wind and solar. Although wind and sun maybe available in abundance throughout the country yet it requires priority access to the grid thus making the grid a weak link in energy security [16].

Energy policies forced into effect by governing bodies answer questions posed by barriers and the aim at each level of jurisdiction is to be at sync with the other levels. In the U.S. there are three levels which actively take part in energy policy decision makings, Federal, state, and local jurisdiction. All the levels face a variety of challenges but work in tandem by making use of the strengths each level possesses. We take a closer look at these three levels in the proceeding sections [17].

### 2.1.1 Federal Level

The federal government can implement decisions at a large scale and thus sets standards and specification for the whole country. This makes it simple for companies to market their products in all states because once a standard is set the specifications of products either do not vary or vary insignificantly. Federal level has the power to offer energy performance related incentives in the early stages of production to ease commercialization process of energy efficient products. They also help organizations identify and execute energy policies by providing technical expertise. One of the major challenges the federal level faces is its low capability of tailoring needs of specific states or regions. Thus, need for the state level of jurisdiction arises [17].

### 2.1.2 State Level

This level of jurisdiction has a broad reach and ability to tailor policies for the economic development of a region in a sustainable manner. States support local industries to thrive by customizing incentives according to the needs of the state and thus attracting the best investments. The amount of energy saved in dollars forms the public benefit funds (PBF) or system benefit charges (SBC) of the state demonstrating the states effort in climate and further encouraging investments from private firms. Energy codes is an aspect which is the responsibly of the state and saves a lot of energy across many states [17].

### 2.1.3 Local Level

It fine tunes the statewide policies at a micro level. This is possible since local jurisdiction is well equipped with the knowledge of community's needs. The needs of a society are more closely met by local jurisdictions, but they lack the desired funding needs and reach in terms of area. Building codes completely come under local and state levels with the federal level only acting as a support mechanism for reward and technical assistance. Local levels have the ability to establish codes if the state has not mandated one, and more frequently these codes are more stringent than state level building codes. Local authorities enforce the code well and lead by example for public and private buildings to get certificates for high efficiency through U.S. Green Building Council's program for Leadership in Energy and Environment Design (LEED) energy plan [17].

In the 1970s, California passed statewide building codes and appliance standards. This stabilized the energy usage per capita related to buildings for well over three decades between early 1970's and late 2000's.  This can be observed in Figure 2.1.

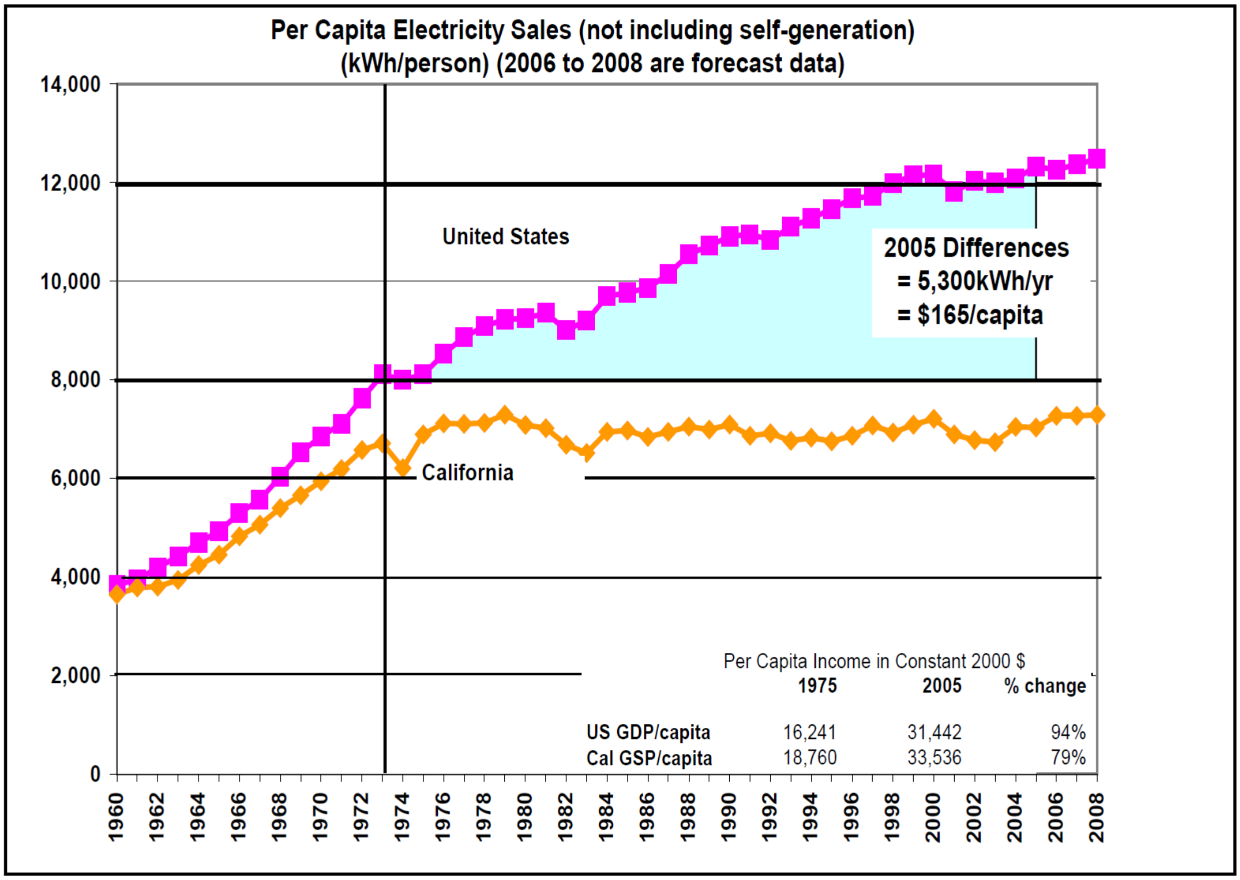


**Figure 2.1:** Per capita electricity usage in California and USA [17].

## 2.2 Energy Efficiency Related Policies

Building sector remains one of the biggest sources of primary energy consumer and is a catalyst to development of power plants. To reduce the energy demand and attributable anthropogenic GHG emissions the following types of policies work the best [17].

- Building codes: A proper building code improves design of the building and optimizes the long-term energy needs.
- Appliance standards: States mandate minimum efficiency levels for appliances
- Labels and consumer information: Gives the customer an informed choice on energy demands related to appliances and buildings.
- Rewards: Given in the form of tax exemptions, incentives, tax credits, etc. The rewards support transition to energy efficient futures.

- Research and Development: These policies accelerate invention of energy efficient technologies.

### 2.2.1 Building Energy Codes

Building codes are state laws, a legal instrument effective in a state or local unit of a government that must be adhered to. The conformity to these codes makes the premise fit for occupancy and use. The federal level of jurisdiction does not have power to impose energy codes, but they create model energy codes which can be adopted by states. The codes can either be adopted by state from model energy codes or they can create a new code of its own depending own prevalent climatic, economic, or technological state of the region. A typical energy code considers wall, floor, window, ceiling insulations and leakages related to ducts and air. There are standards of equipment and lighting also included in the code which are used inside the buildings [18].

### 2.2.2 Purpose of Energy Codes

Energy code sets a minimum required efficiency level for a new or renovated building. They form a subset of building codes which is also comprised of fire, electrical, plumbing and construction codes. Using energy code, building operations becomes more efficient and emits less greenhouse gases. This is accompanied by reduced energy expenses and a dwindling need to depend on imported oil. Amidst fundamental issues of environment, economics, and energy costs, building energy codes are crucial for sound public policies [19].

### 2.2.3 Advantages of Building Energy Codes

The energy code represents a tremendous avenue of energy and cost savings when applied to any building. It is estimated that between 2010 and 2040, savings worth $126 Billion is possible. 841 MMT of $CO_2$ emissions could be avoided and 12.82 quads of primary energy could be saved. As defined by statute, the model energy codes are the International Energy Conservation Code (IECC) for residential buildings, and ANSI/ASHRAE/IES Standard 90.1 for commercial buildings (42 USC 6833)

It is expected that by 2035, 75% of the building stock in USA will be either new or renovated and studies find that 80% of energy used by a building is governed by an energy code which significantly boosts savings by reducing power demand, thus minimizing environmental impacts. The benefits of energy code is felt at all levels of a community. The customers gain confidence that the energy bills would be low if energy codes are applied, the construction firms know that they are meeting minimum energy efficiency requirements and they have a written document to rely upon while marketing their buildings. Utilities get hold of cost-benefit data to plan their investments on efficiency programs and can provide better predictions and decreased peak demands [19].

### 2.2.4 Role of Department of Energy (DOE) in Building Energy Codes

The law (the Energy Conservation and Production Act (ECPA)) requires DOE to carry out the following two activities:

1. For new federal commercial, manufactured homes and residential buildings DOE must establish a minimum energy efficiency standard. Compliance to the standards is mandatory [20].
2. DOE must evaluate whether new editions to ASHRAE 90.1 and IECC or any successor of 1992 MEC (Model Energy Code) when revised, improves energy efficiency. DOE publishes its findings and analyses through BECP (Building Energy Codes Program) and publishes the rules. [ASHRAE 90.1 is meant for commercial and multi-family high-rise residential buildings & IECC is meant for low-rise commercial buildings] [20].

Once the Secretary has published that the new editions or revisions to codes improves energy efficiency of the buildings then within two years of its publication each state should compare its codes to the new editions or revisions. This must be done through a public notice or hearing in writing based on evidence available to the public. If the state determines that the new codes do not improve the existing energy codes, then they are not needed to adopt it but must provide reasons and evidence available to public and in writing. However, if the state finds that the revisions improve energy efficiency, then within two years of the publication of the revisions, the state must certify that it has matched or exceeded the requirements through a demonstration. There are provisions available to extend the deadline for matching or exceeding standards if efforts were made in good faith. Also, the DOE is required to assist the states in adopting the new standards in a hassle-free manner by providing technical expertise [20].

### 2.2.5 Building Energy Codes Program (BECP)

With the BECP, the United States established a vision to use minimum amount of energy in buildings for the activities and comfort of the occupants [21]. Although the BECP does not create or enforce energy codes yet it helps in standard development. The mission of the program is to help building owners adopt to energy codes by providing tools and support to increase compliance rate. A healthy compliance rate indicates maximum cost-effective realization of energy efficiency with provision of a safe and sustainable dwelling condition for all occupants.

The BECP does not have all the resources at hand required to achieve the mission of energy conservation and efficiency thus its acts in a manner to catalyze a transformation in a market by conducting relevant research and disseminating techno-economic research backed with solid data. Energy codes are evaluated for technical changes and cost effectiveness and its value is maintained amongst all stakeholders. This requires creation and update of tools and materials and assurance that energy codes are in sync with other building codes.

BECP assumes leadership position to encourage exchange of information and encourage the state and local government in activities which adopt and enforce energy codes. It convenes forums for discussion of best practices and adoption and compliance of supporting resources. BECP actively participates in forums where energy codes are discussed, developed and approved. The program believes in sharing knowledge it possesses with other organizations and learning from them on aspects which could evolves all aspects of energy codes.

BECP is a team within the U.S. Department of Energy's Office Energy Efficiency and Renewable Energy and a key component of Building Technologies Office (BTO) which is committed in tracking and reporting its progress while seeking objectives of cost-effective energy savings and reduction in building energy use intensity [20].

### 2.3 Federal Energy Management Program (FEMP)

DOE is required by section 305 of ECPA, as amended, to create energy efficiency standards, covering all new buildings under federal use. The measures must be techno-economically justifiable. The standards must incorporate energy savings and renewable energy specifications which either meet or exceed the referenced voluntary consensus energy codes. For new federal buildings energy efficiency performance standards should be such that the buildings consume 30% lesser energy than what is referenced in the reference codes (ASHRAE 90.1 for commercial buildings and IECC for low rise residential buildings). Based on the cost-effectiveness of the revised codes and within a year of its publication, the DOE must decide whether to adopt the revisions for federal buildings. Section 306(a) of ECPA requires architects of federal buildings to comply with the energy efficiency standards as established . Further , Section 306(b), bars any funding to be endowed to the new buildings until the requirements of energy efficiency standards as established are either met or exceeded.

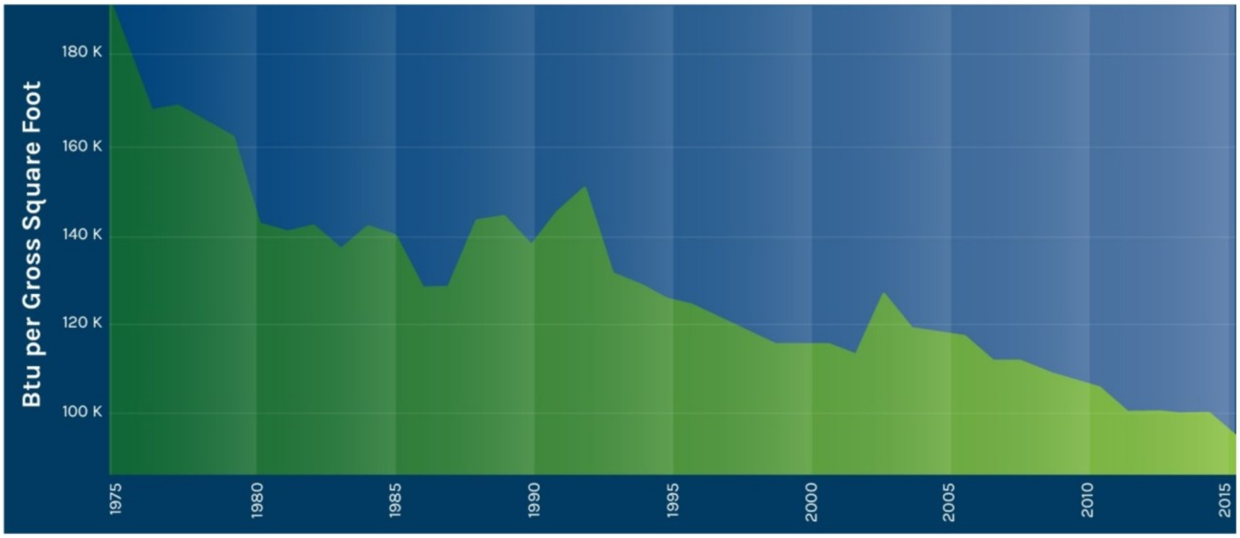


**Figure 2.2:** Energy intensity of federal facilities between 1975 and 2015 [22].

Figure 2.2 shows that energy intensity in federal facilities have reduced by 49% between 1975 and 2015 which demonstrates that the government is taking energy as a serious issue and setting high standards. This becomes more important when we add the fact that the federal government is the largest consumer of energy in the United States with energy-utilizing buildings surpassing 350,000 and vehicles beyond 600,000. 36% of the total energy delivered to sites of federal government is consumed by buildings and facilities.

Key services with which FEMP caters to agencies by meeting their energy and water reduction goals are listed below [22]:

- FEMP issue legislative and executive guidance
- Facilitates in integrating technology.
- Leverage of funding sources
- Provision of technical assistance
- Track accountability of agencies

- Development of accredited training

The objective of FEMP is to equip federal agencies to meet and exceed energy targets, with affordable solutions, creation of public-private partnerships and identify best practices, all working in tandem with FEMP stakeholders.

Meet the stakeholders:

- Agencies: FEMP provides required project support and technical assistance along with tracking annual progress to meet legislative and executive aspirations.
- Congress: Supports legislative initiatives and reports annual progress.
- Industry: Uses private sector technologies to find solutions in the federal workspace.
- National Labs: Works together to develop training and tools for the use of agencies.
- White House: Compile agency score cards and implantation of executive orders.

FEMP works towards energy independence, resiliency and security through the following focus areas:

1. Strategic Programming and Integration Planning
2. Facility and fleet optimization
3. Energy and Water resilience and security
4. Energy and project procurement development services
5. Federal leadership and engagement

### 2.4 Compliance of Energy Codes

Once the building owners have decided to follow the energy codes, they now must show their compliance which is done in the following two ways [23]:

1. **Perspective Path**: The building energy codes have a set of defined values for each individual component in the building. For example, all the glass panes have a fixed R-Value or there is defined economizer requirements in HVAC systems. Compliance to each of those values of individual systems is the perspective path.

2. **Performance based approaches:** To show compliance, the building owners can trade-off between certain criterions i.e., requirements of some of the systems are not but in other systems the perspective requirements are exceeded. Thus, the excess of the latter system makes up for the shortfall of the former system. There are two performance-based approaches:

    a. **Energy Cost Budget (ECB) method:** A baseline is established to just meet the perspective requirements. It is basically a clone of the proposed design. A building is deemed compliant with energy code ASHRAE 90.1, when its annual energy cost is less than the baseline building. This approach is often referred to as dependent baseline.

    b. **Performance Rating Method (PRM) method:** This approach is often referred to as 'Appendix G' due to its position in the performance standard. Being a more independent and a stable baseline, its characteristics is based on standard practice. Efficiency value of the codes are held stable, and performance of the buildings are evaluated by the amount with which building systems efficiency or value exceeds the baseline. This excess value must be commensurate for the code year it is being evaluated. Credits are awarded for exceeding requirements of the standard and for exceeding standards which are not regulated by the standards. For example, the ECB does not award credit for well positioned and optimized window areas but credits for this are available in PRM method.

### 2.5 Barriers to Building Energy Transition

Barriers to energy transitions are the factors which resist the adoption of new policies, energy codes, energy conservation measures or use of energy efficient equipment to achieve a nations energy goal. There are barriers present in all the sectors which use energy and building sector perhaps having the most compared to its counterparts. Koeppel has divided the barriers into six types and suggested some remedies for them [23]. They are as follows:

1. **Economic/Financial:** The low-income group do not have the spending power to purchase energy efficient equipment and a heavy down payment discourages other interested parties. Many customers are also suspicious of the payback period of these purchases. The economies which are expected to aggressively expand their infrastructure face trouble

while addressing this challenge internally. Tax rebates and subsidized loans are some of the remedies which have been suggested to alleviate this barrier.

2. **Hidden costs/benefits:** Factors such as poor power quality in some developing and underdeveloped nations, risks intertwined with overhauling existing technology and factors as basic as unavailability of compatible power sockets has adverse impact on the decision of the customer. Implementation of wide scale appliance standards and building energy codes are suggested by Koeppel as remedies.

3. **Market Failure:** Energy efficiency is challenged by budgets constraints at every level of implementation. There are conflicting interests of governments which sometimes misplace the allocation of subsidies and jeopardizes the goals of energy efficient policies and equipment. The utility sector was not obliged to consider demand side management a few years back and even today it is limited to advanced countries of the world. Remedies suggested are product standards, economic instruments, and incentives.

4. **Behavioral and organizational:** Perhaps the most mercurial aspect in energy efficiency transformation is the nature of individuals who have varying lifestyle and comfort parameters. Some of the low hanging fruits can simply be achieved by spreading awareness amongst end users. Affluent people generally consume the highest share of energy but are not keen to reduce energy consumption simple because it takes a small portion of their spending capacity. The remedies suggested are voluntary agreements and information and training programs.

5. **Information:** Priority of access to grid for every region over priority to provide access to the grid combined with energy efficiency is the national challenge that all the developing and underdeveloped nations face today. It is due to the ignorance in responsible organizations about energy efficient techniques and methods to overcome barriers. Awareness raising campaigns and trained building professionals are suggested remedies.

6. **Political and structural:** Government's indifference towards energy efficiency, ability to enforce policies due to existing barriers like support of coal lobbyists to the government in some nations or simply corruption. Suggested remedies are improving implementation of standards and public leadership programs.

# CHAPTER 3
# BUILDING ENERGY MANAGEMENT

Building energy management is a process of managing energy utilization in large commercial and residential buildings. The principal objectives of this process are to improve energy efficiency and reduce energy consumption in the building without compromising on the comfort and functioning of its occupants, and also maintaining a healthy indoor environment [24]. With effective building energy management, there is a possibility of up to 15% energy savings in buildings [25] [26].

Effective management of energy consumption is contingent on:

- Incorporating energy efficient technologies
- Analysis of performance of the Building Energy Management Systems (BEMS)

An example of BEMS can be found in the use of appliances in buildings. Studying interaction between appliances in their use and control yields opportunity for energy savings during their normal operation phase. There is an increasing reliance on building energy management system to obtain the results of interaction between appliances, although the maintenance of this system is often neglected. The BEMS needs regular tune ups and upgrades at regular intervals for consistent performance [27]. Evaluation of the BEMS to optimize energy consumption depends on the analysis of performance of energy consumption and investigation of operation strategies. The performance and indoor air quality of the building further relies on the following attributes [28]:

- Geographic Location

  Depending on which part of the world the building is located, there are varying air-conditioning and Indoor Air Quality (IAQ) requirements. In colder regions, heating consumes a lot of energy and in hot regions, cooling requirement is more. Some places of the world have bad air quality, so there is frequent need to filter, recirculate and condition the fresh air coming into the buildings through the supply ducts and air handling units.

- Building Type

  There are different purposes served by buildings; some are schools, hospitals, national labs, government offices, etc. Each building has unique energy requirements. Labs will require fresh supply of air round the clock, hospitals maintain the optimum temperature and air quality for comfort of its residents and schools and government offices can reduce their energy usage at nights by using setbacks.

- Building Size

  The size of the building defines the amount of energy required for its proper operation, and with increase in size, the need for fresh air, lighting, appliances, etc., also increases. Additional fresh air means, more heating or cooling requirements and thus more energy and emissions.

- Age of Building

  This is a major factor when energy consumption is considered. Older buildings tend to consume more energy and have more leakages which makes them energy inefficient. It is advised to retrofit the old facilities with new energy efficient equipment; for example, replace incandescent light with LEDs. The HVAC systems in the old buildings are also very inefficient when we compare them to the newer HVAC systems in modern buildings that are equipped with sensors and demand control ventilation.

- Occupancy Schedule

  Different types of buildings have different energy needs at different times of the day. Typically, energy demands for schools and government facilities peak at day time. The energy need is low at night when the temperatures are rolled back to use less energy and is set to thermal comfort temperature when it is about to be occupied. But labs, hospitals and manufacturing facilities demand almost the same amount of energy round the clock, so different operating conditions are prevalent for all types of buildings.

- Maintenance and Operation

  As the building gets older, need for maintenance becomes more frequent, the equipment begins to wear out and become more inefficient. Energy audits and preventive maintenance are best ways to control these inefficiencies. Operation strategies like demand response and best practices like de-lamping over lit areas helps keep energy consumption low in buildings.

### 3.1 Steps Involved in Building Energy Management

Building energy management starts with setting goals and objectives of energy management tasks, such as a 5% electricity reduction within a year. Then a survey of energy management system of the whole facility is done. For this, necessary building documents are studied, building walkthroughs are carried out and the building management system is reviewed. The information collected after the steps are used to develop a chronological scenario for a system (say an HVAC system) which needs to be upgraded. The outline of the parameters representing the system (obtained through walkthroughs and examination of system input-output from servers) coupled with weather data file forecasts the performance trends of the system. This will lead to two outcomes which strengthens energy optimization:

- Point out prevailing problems in the system.
- Identify scope for upgrades of the system [24].

The building energy management encompasses the following tasks [29].

- Auditing energy usage in the building and maintaining an energy inventory.
- Establishing procedures to setup energy targets and baselines.
- Benchmarking buildings of similar envelope, which includes size, location, occupancy, etc.
- Analyzing short-term and long-term energy usage patterns and deviations.
- Setting up energy conservation goals and procedures.
- Improving operations and maintenance of energy-consuming equipment (such as HVAC) and devices (such as computers), appliances, lighting and insulations.
- Engaging occupants in energy conservation activities.
- Identifying, approving, and managing energy efficiency improvement projects on the premise.
- Converting to sustainable and renewable energy sources, such as solar panels.

. The benefits of building energy management are listed below.

- Improved operational efficiencies.

- Decreased energy intensity.
- Energy data for fact-based decisions.
- Support for organizational and cultural change.
- Drivers for organizational integration.
- Reduced environmental impacts.
- Competitive advantages over peers that neglect resource management.
- Visible demonstration of social responsibility.

### 3.2 Breakdown of Total Energy Consumption

Figure 3.1 shows energy breakdown of a building located in California. The total conditioned area for the building is 16,000 $m^2$ and it is occupied between 7 am to 6 pm on weekdays. It is a university building built in the year 2005 [30].

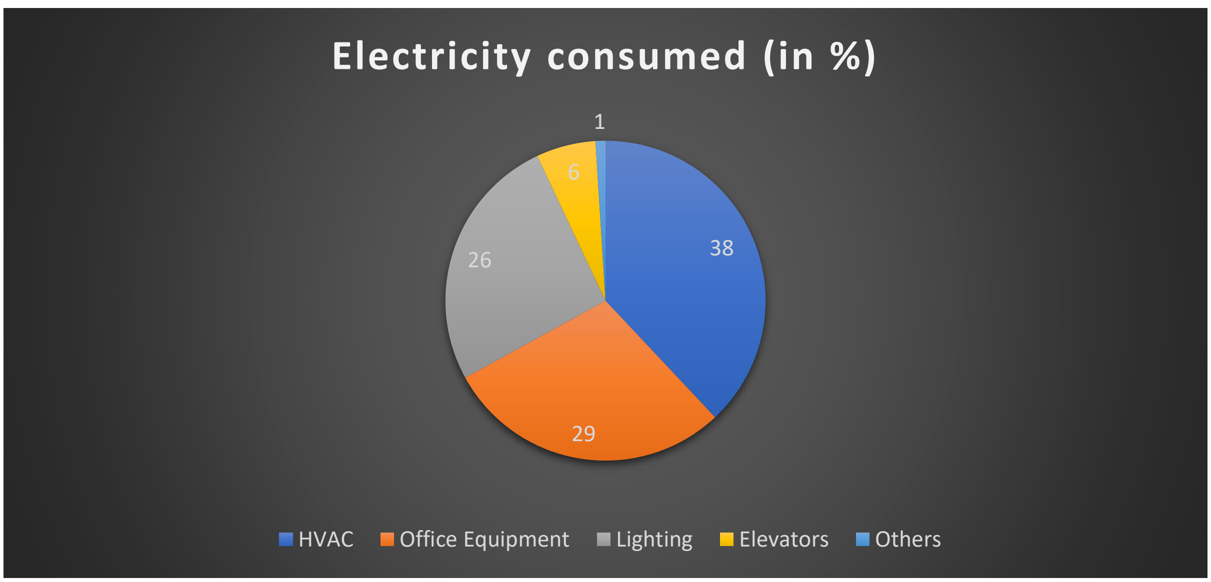


**Figure 3.1:** Electricity consumption breakdown into subsystems for a university building.

Figure 3.1 represents the energy data for a typical university building, but it varies for various types of buildings. A commercial building might have a higher lighting demand, or a lab might have higher ventilation demand. But the figure above is a good estimate for the breakdown of energy consumed by various subsystems.

### 3.3 Evaluation of Energy Losses in a Building

Building energy management is managing the use of electricity in residential and commercial buildings with improvement in energy efficiency and reduction of energy consumption. Identification and prevention of energy losses is one way in which energy consumption is reduced with limited capital expenditure. The list of avenues of energy losses listed below is from a case study discussed later in this section. The losses were detected through preliminary energy audits and building walkthroughs [31]. A closer examination of theses energy losses using Total Quality Management tools like affinity diagrams and Pareto Charts shows the significance of HVAC and building envelope to boost energy efficiency and reduce energy consumption. The energy audit and the walkthroughs uncovered the following avenues of heat losses:

- Unconditioned spaces not isolated properly.
- HVAC economizers are not programmed and working improperly.
- Manufacturer HVAC maintenance recommendations not followed.
- Air filters based on the equipment's maintenance program for all HVAC systems are not clean and replaced.
- Chillers not running in their most efficient zone.
- Multiple cooling towers not in operation.
- Chillers not tuned and maintained.
- Chilled water insulation not maintained.
- Pneumatic thermostats and controls not calibrated.
- Compressed air leak audits not performed.
- Exhaust fans not in shutdown mode during off hours.
- All compressed air leaks are not fixed when pneumatic controls are used.
- Gas heating systems not tuned every two years.

- Conditions of hot water and steam pipe insulation not evaluated and tagged where they can be improved.
- Steam trap audit and repair program not developed.
- Insulation on steam and hot water lines not installed.
- Failed or broken steam traps not repaired or replaced.
- Building walls, roof, windows, and doors not assessed for leaking air or infiltration.
- Missing or damaged caulk and weather stripping not repaired.
- Blinds not utilized to reduce heat gain and heat loss during cooling and heating seasons.
- Broken or damaged windows and doors not repaired.
- Window film not installed.
- Double paned windows and glass doors absent.
- Cleaning and maintenance plan for refrigerators and freezers not implemented.
- Strip curtains on walk-in cooler and freezer doors not installed.
- Computer and PC monitors not set to sleep mode when not in use.
- Cooling systems in drinking fountains not turned off during off hours.
- Smart strip surge protectors for office equipment not utilized.
- Sensor operated faucets and flush valves not used in restrooms.

### 3.3.1 Affinity Diagram

It is a powerful tool to group data in packets which are closely related [32]. This helps in systematic analysis of the problems and assists in Pareto analysis to find the major few causes of an event.

For our purpose we can group the HVAC data in the following categories:

1. HVAC cooling and ventilation
2. HVAC Controls

3. Heating systems

4. Building Envelope

5. Others (Appliances, Food Services, Office Equipment, Restroom sensors)


**Figure 3.2:** Affinity diagram for energy losses.

### 3.3.2 Pareto Analysis

This quality tool states that for 80% of the causes, 20% of the factors are responsible. Thus, the 80-20 rule shows that there are a major few reason responsible for maximum impact [33].

The affinity diagram has grouped factors responsible for energy losses into five clusters. For Pareto analysis, we expand the last cluster, 'others' into the following categories:

1. Office equipment
2. Appliances
3. Food services
4. Restroom sensors
5. Miscellaneous

The table below shows the number factors in each of the clusters and the percentage impact they have on the energy loss for a commercial building.

**Table 3.1:** Table used for Pareto analysis of avenues of heat losses in a commercial building.

| Avenues of Losses | Number of factors | % Contribution |
|---|---|---|
| HVAC Cooling & Ventilation | 8 | 27.5862069 |
| Building Envelope | 6 | 20.68965517 |
| Heating Systems | 5 | 17.24137931 |
| HVAC Controls | 4 | 13.79310345 |
| Office Equipment | 2 | 6.896551724 |
| Appliances | 1 | 3.448275862 |
| Food Services | 1 | 3.448275862 |
| Restroom Sensors | 1 | 3.448275862 |
| Miscellaneous | 1 | 3.448275862 |
| Total | 29 | 100 |

For our analysis we have listed 29 factors of energy losses in a building and categorized them under 9 headings to carry out the Pareto analysis. Figure 3.3 represents the Pareto chart.

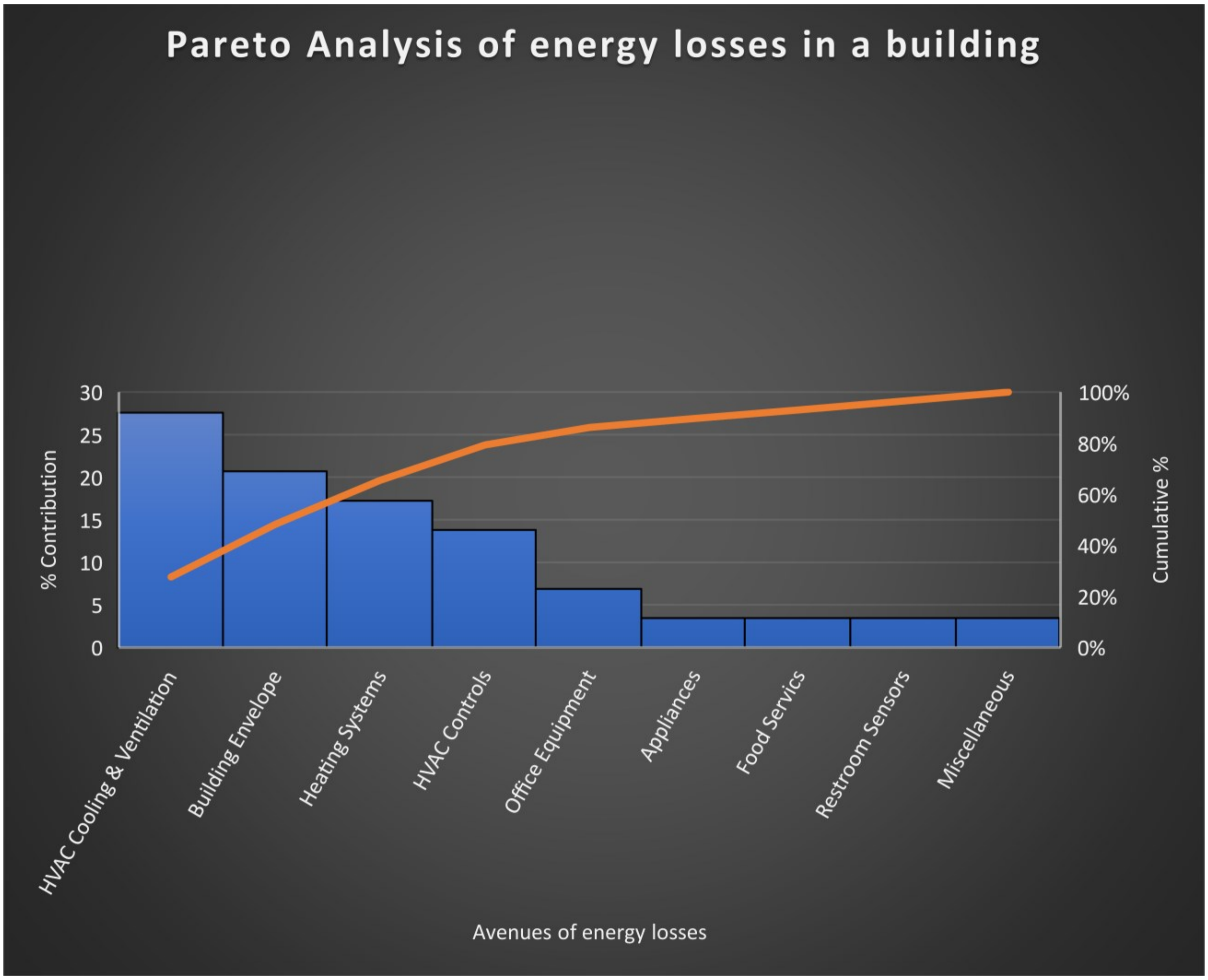


**Figure 3.3:** Pareto chart for avenues of heat losses.

### 3.3.3 Analysis of Pareto Chart

HVAC factors and building envelope are responsible for approximately 80% of the causes of energy losses. To conserve energy, these are the two factors that need to be prioritized. Both the causes of energy loss are closely related. Maximum energy consumption in a commercial building is through HVAC and the Pareto analysis also indicates that this is the area that needs special attention with regards to energy conservation and efficiency.

## 3.4 Strategic Energy Management Plan (SEMP)

The Office of Energy Efficiency and Renewable Energy of the US Department of Energy states that Strategic Energy Management Plan (SEMP) is a systematic process that enables an organization to enforce energy management actions and achieve energy targets efficiently. The SEMP facilitates the requirements needed for blending energy management practices into everyday operations which contributes to continuous improvement. The key elements of a successful SEMP are benchmarking, tracking and monitoring building energy collection of energy related data. The components of SEMP are shown in Figure 3.4. It starts with a commitment from the upper management. It is recommended that organizations write down their SEM Plans to make it consistent with the objective statement of energy management. A written document reduces over-allocation of resources and has a status in the organization required to streamline some bureaucratic processes [34].

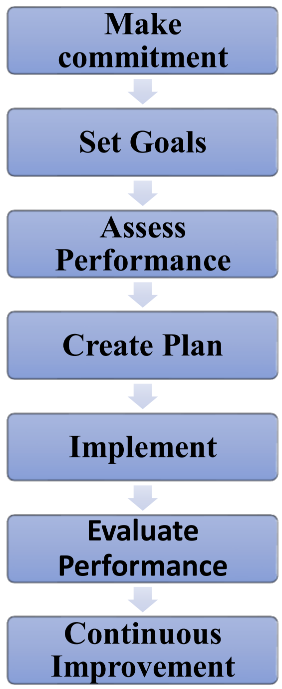


**Figure 3.4:** Components of SEMP.

Below is an outline of SEMP established by the University of Michigan across its three campuses for becoming carbon neutral through efficient energy management and conservation measures.

- Make a commitment: The President of University of Michigan pledged for the entire University to go carbon neutral in all scopes by 2040 [35].
- Set goals: Here are the goals set by UM-Dearborn from the SEMP [31].
    - Specific: Reduce natural gas consumption by 10% and electricity by 8%.
    - Measurable: $200,000 worth of annual energy savings.
    - Aligned: Completely in sync with UM-President's commission on carbon neutrality.

- Realistic: The estimated budget for the energy projects is \$233,000 annually.
- Time bound: The goals are set to be achieved in 5 years.

- Assess performance: Year 2018 was selected as the benchmark year for which all energy costs and savings would be compared to. Energy usage, costs, and energy performance of the University for the baseline year was thus collected.
- Create plan: To create plan for improving energy efficiency and reducing energy losses, preliminary energy audits and building walkthroughs of the whole campus at UM-Dearborn was performed. We analyze the case of a particular building, 'IAVS', details of which are listed in Table 3.2 and 3.3.
- Implement: The suggestions found from the energy audits and walkthroughs are funded and implemented in this stage.
- Evaluate performance: The performance of the implementations is continuously measured and improvements are done based on the feedback.
- Continuous improvement: SEMP is not a one-time process and it is continuously improved and analyzed in a closed loop.

### 3.4.1 A SEMP Case Study

This discusses SEMP applied to the IAVS building located on the University of Michigan-Dearborn campus. Built in 2007, IAVS (Institute for Advanced Vehicle Systems) is one of the newest buildings on the Dearborn campus and has tremendous potential to be LEED certified. It has some energy efficient systems like Building Management System, VAV (Variable Air Volume) System, outdoor reset for water heating, and double paned windows. A few basic information about the IAVS building are given in Table 3.2 and electricity use in the building in the benchmark year 2018 is listed in Table 3.3.

**Table 3.2:** Basic building information.

| Building Name | IAVS |
|---|---|
| Year Built | 2007 |
| Gross Square footage | 44,544 |
| Major renovations | Not any |
| Electric sub-meter | Present |
| Natural Gas sub-meter | Absent |

**Table 3.3:** Amount and cost of electricity consumed by IAVS building in the baseline year 2018.

| Month | KWH | Cost (in $) |
|---|---|---|
| Jan | 89,855 | 8,021 |
| Feb | 100,740 | 8,993 |
| Mar | 124,734 | 11,135 |
| Apr | 123,642 | 11,037 |
| May | 139,108 | 12,418 |
| Jun | 148,738 | 13,278 |
| Jul | 171,501 | 15,310 |
| Aug | 147,353 | 13,154 |
| Sep | 140,293 | 12,524 |
| Oct | 132,459 | 11,824 |
| Nov | 120,906 | 10,793 |
| Dec | 107,804 | 9,623 |
| Total | 1,547,132 | 138,109 |

#### 3.4.1.1 Strategies to Reduce Energy Consumption in IAVS Building.

The energy team found avenues of inefficiencies which includes over-utilization of lights, absence of blinds on windows, no occupancy photo-sensors, and some leakages on the doors. After building walkthroughs the energy team made the following suggestions to improve the energy usage.

1. Installation of DCV systems (Demand Control Ventilation).
2. Implement a hot water reset for boilers.
3. Implement a chilled water reset.
4. Reduce minimum outside air intake.
5. Install insulation on steam and hot water pipes.
6. Install occupancy sensors.
7. Convert all lights to LED.

For representation, we will discuss one of the suggested improvements and look at its cost and payback period. In section 3.4.1.3, we will add up the total costs of implementing suggestions and their payback periods. Sample calculation for installation of DCV system is shown below. Values of amount of energy conserved and payback period for other strategies are calculated similarly in the Energy Management Handbook of University of Michigan-Dearborn.

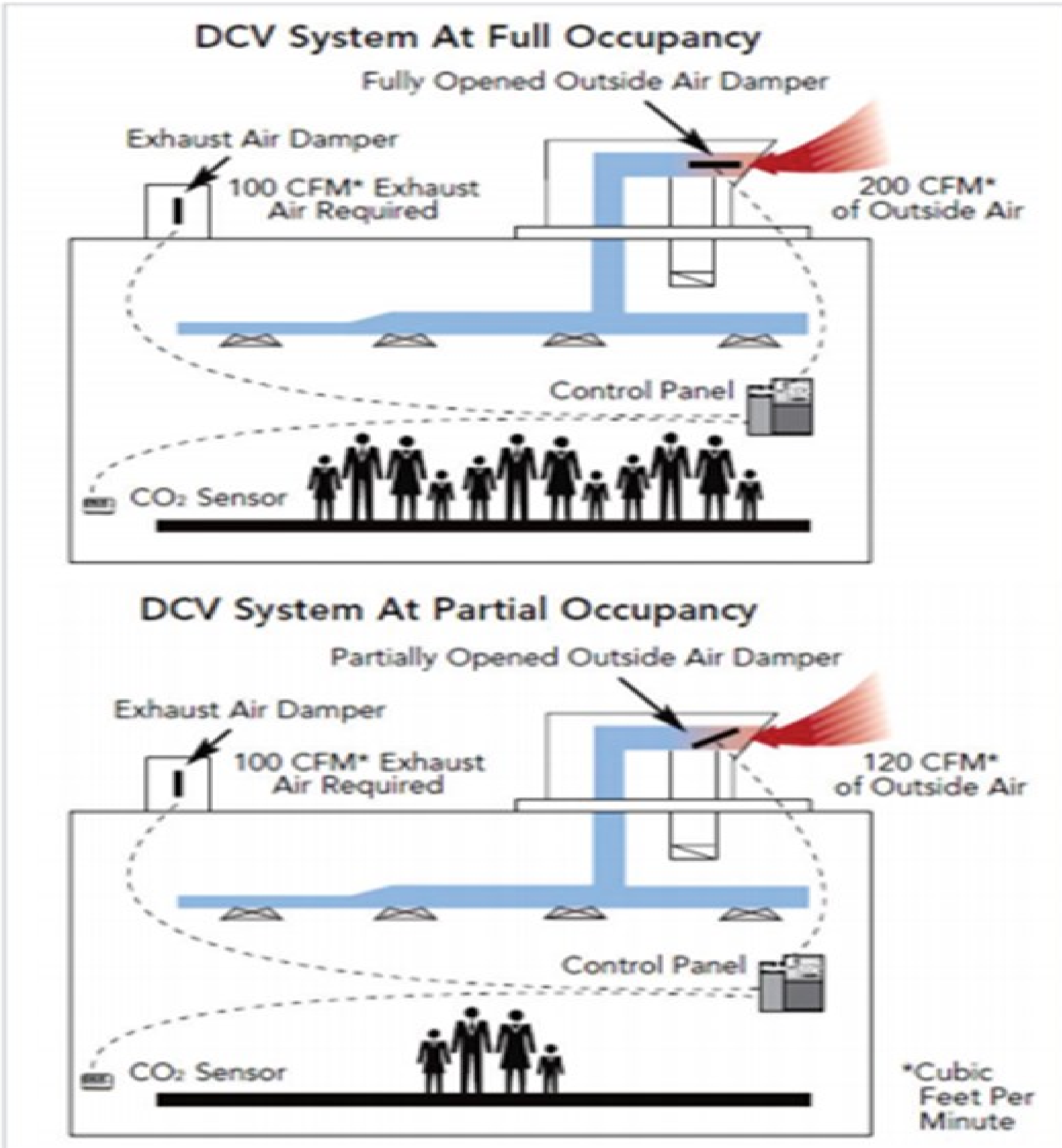


**Figure 3.5:** Working of a DCV system.

A DCV system on installation at an average reduces need for outside air by 55%.

Current outside air requirement by IAVS Building = 26,555 cfm

Proposed outside air requirement after DCV installation = 26,555(1-0.55) = 11,950 cfm.

Here are some more data which will be used in calculations for energy savings and cost savings.

**Table 3.4:** Details used for sample calculation.

| | | |
|---|---|---|
| Total min design outside air | 26,555 | cfm |
| Average summer/cooling hours | 1,042 | hrs |
| Average winter/heating hours | 1,844 | hrs |
| Average summer outside temp | 89 | F |
| Summer indoor design temp | 74 | F |
| Enthalpy summer indoor | 28.6 | Btu/lb |
| Enthalpy summer outdoor | 34.2 | Btu/lb |
| Winter indoor design temp | 76 | F |
| Average winter outdoor temp | 35 | F |
| Gas Cost | 4.5 | $/MMBtu |
| Electricity cost | 0.0893 | kwh |
| Heating system efficiency | 84% | |
| Cooling system efficiency | 0.75 | KW/ton |

The data for enthalpy related to summer indoor and outdoor temperatures are extracted from the psychrometric chart (Figure 3.6).

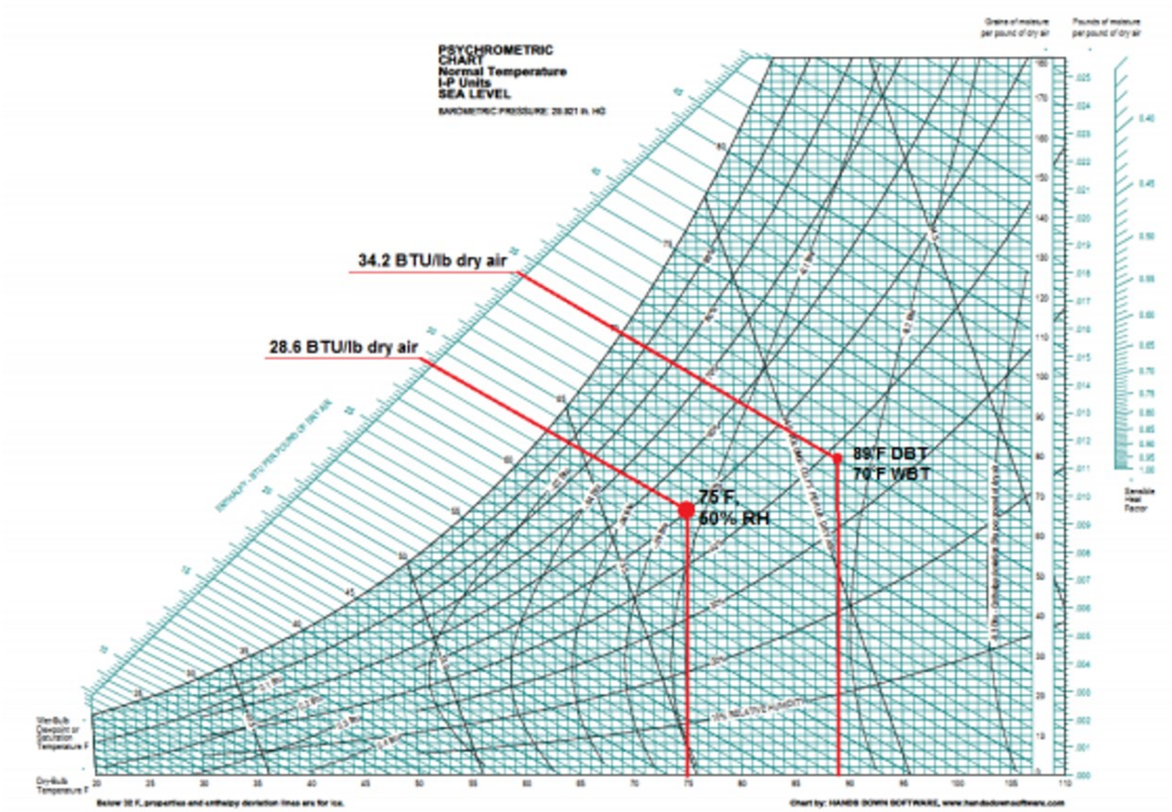


**Figure 3.6:** Psychrometric chart for enthalpy calculation [31].

1. Calculation of energy use in 2018

(a) Summer energy usage:

= Cost of gas x Total min design outside air x Enthalpy difference between summer outside and inside air = 4.5 x 26,555 x (34.2 – 28.6) = 669,186 Btu/hr.

Converting the summer energy usage into tons is done by dividing it by 12000.

= $\frac{669186}{12000}$ = 55.7655 (For simple calculation, we will round this value to 56 Tons)

To find electric energy usage per year:

= Tons x cooling system efficiency x annual summer hours

= 56 x 0.75 x 1042 = 43,764 kwh/year

To find cost, multiply electric energy usage per year and Electricity cost

= 43,764 x 0.0893 = 3908 ($/year approx.)

(b) Winter gas energy use:

= 1.08 x outside air requirement (cfm) x (Temperature difference between winter inside and outside air) x (annual winter hours) / (1,000,000)

= 1.08 x 26,555 x (76-35) x 1,844 / 1,000,000 = 2,168 MMBtu/year

Winter gas energy cost = (Winter energy use / heating system efficiency) x gas cost

= (2,168/ 0.84) x 4.5 = 11,614 $/year

Therefore, total energy cost = 3,908 + 11,614 = 15,522 $/year

2. Calculation for proposed energy usage with DCV installed.

(a) Summer gas energy usage:

= Cost of gas x Total min design outside air with DCV x Enthalpy difference between summer outside and inside air

= 4.5 x 11950 x (34.2 – 28.6) = 301,140 Btu/hr

Converting the summer energy usage into tons is done by dividing it by 12000

$= \frac{301140}{12000}$ = 25 Tons approx.

To find electric energy usage per year:

= Tons x cooling system efficiency x annual summer hours = 25 x 0.75 x 1,042 = 19,537 kwh/year

To find cost, multiply electric energy usage per year and Electricity cost

= 19,537 x 0.0893 = 1,744 $/year approx.

(b) Calculation for winter gas energy use:

= 1.08 x outside air requirement (cfm) x (Temperature difference between winter inside and outside air) x (annual winter hours) / (1,000,000)

= 1.08 x 11,950 x (76-35) x 1,844 / 1,000,000 = 976 MMBtu/year approx.

Winter gas energy cost = (Winter energy use / heating system efficiency) x gas cost

= (976/ 0.84) x 4.5 = 5,228 $/year approx.

Therefore, total energy cost = 1,744 + 5,228 = 6,972 $/year approx.

With the implementation of DCV, the savings are tabulated in Table 3.5.

**Table 3.5:** Proposed electricity, gas and cost savings.

| | | |
|---|---|---|
| Current electricity usage | 43,764 | kwh/year |
| Proposed electricity usage | 19,537 | kwh/year |
| Savings | 24,227 | kwh/year |
| Current Gas usage | 2,168 | MMBtu/year |
| Proposed gas usage | 976 | MMBtu/year |
| Savings | 1,192 | MMBtu/year |
| Current total energy cost | 15,522 | $/year |
| Proposed energy cost | 6,972 | $/year |
| Savings | 8550 | $/year |

There are associated installation costs and some rebate provided by the utility company which are listed in Table 3.6.

**Table 3.6**: Installation costs and rebates offered by utility company.

| | | |
|---|---|---|
| No of $CO_2$ sensors required | 8 | units |
| Cost of one sensor | 350 | $ |
| Total cost of sensors | 2,800 | $ |
| Cost of installation | 1,200 | $ |
| Cost of programming | 1,000 | $ |
| Cost of commissioning and startup | 750 | $ |
| Soft costs incurred' | 2,500 | $ |
| Total installation cost of DCV | 8,250 | $ |
| Rebate by utility company | 506 | $ |
| Effective total implementation cost | 7,744 | $ |

The simple payback period, obtained by dividing the effective total implementation cost of DCV system with annual energy savings, is 0.9 years.

#### 3.4.1.2 Impact of Proposed Strategies on Energy Consumption and Costs

Table 3.7 shows the impact of different strategies on energy savings and costs as estimated by the energy team. These values are referenced directly from the data published in the energy management handbook.

**Table 3.7:** Estimated impact of strategies on energy and cost savings.

| Strategy | Electricity Savings (KWh) | Gas Savings (MMBtu) | Cost of Implementation ( $) | Payback Period (Year) | Total Savings (in $) |
|---|---|---|---|---|---|
| Install demand control ventilation (DCV) system | 23,969 | 1,193 | 8,250 | 0.9 | 8,529 |
| Hot Water reset | NA | 225 | 221 | 0.2 | 1,014 |
| Chilled water reset | 8,470 | NA | 780 | 0.5 | 756 |
| Install programmable thermostat on vestibule heaters | NA | 87 | 977 | 2.5 | 390 |
| Insulation on steam and hot water pipes | | 157 | 2,600 | 2.9 | 707 |
| Occupancy sensors | 6,212 | NA | 5,725 | 6.9 | 621 |
| Lighting upgrade | 32,917 | NA | 18,762 | 3.9 | 5,225 |
| Total | 71,568 | 1,662 | 37,315 | 2.2 | 17,242 |

The savings derived from the strategies is estimated in Table 3.8.

**Table 3.8:** Savings derived from the proposed strategies.

| | Electricity (KWh) | Cost (in $) |
|---|---|---|
| For Baseline year 2018 | 1,547,132 | 138,109 |
| Calculated values after implementation of strategies | 1,475,564 | 12,067 |
| Estimated savings | 71,568 | 17,242 |

From the strategies discussed in this section, a 5% saving in electricity amount and 11% saving in electricity cost for the IAVS building are achievable compared to the electricity consumed and cost incurred in the baseline year of 2018.

# CHAPTER 4
# BUILDINNG INSULATION MATERIALS

The building insulation material forms an integral part of building envelopes. They reduce heat transfer between the indoor dwelling and the ambient. An efficient building insulation material reduces energy consumption, and therefore the operational cost of the building. This is complemented by reduced greenhouse gas emissions.

There are numerous benefits of home insulation. It creates a positive environmental impact, minimizes energy costs, promotes healthier indoor environment, and regulates indoor temperature especially in places with adverse climates. In winters it keeps the house warm and in summer it keeps the house cool thus reducing the need for excess heating and cooling appliances. A layer of insulation also creates a sound barrier, preventing noise from the outside coming in and vice-versa. It restricts vibrations of machines to enter from the partitions of the ceilings and walls. To an extent it absorbs it. A good insulation also prevents entry of moisture between the layer of walls and causing damage. Moisture can creep in from groundwater, rain, and surface water deteriorating the condition of elements of construction. Metals can corrode, painting can be damaged, fungi might proliferate and all of corroborating an unhealthy situation for the users. With less energy required for heating and cooling, the associated carbon footprint and toxins released into the atmosphere are some benefits to the environment [36].

## 4.1 Insulation Layer in a Building Wall

Figure 4.1 shows a typical building envelope in which the insulation panel is located between the inner and outer walls. There are usually air gaps on both sides of the insulation panel. The principal modes of heat transfer from the inside to the outside of the building are conduction in the walls and the insulation panel and convection in the air gaps.

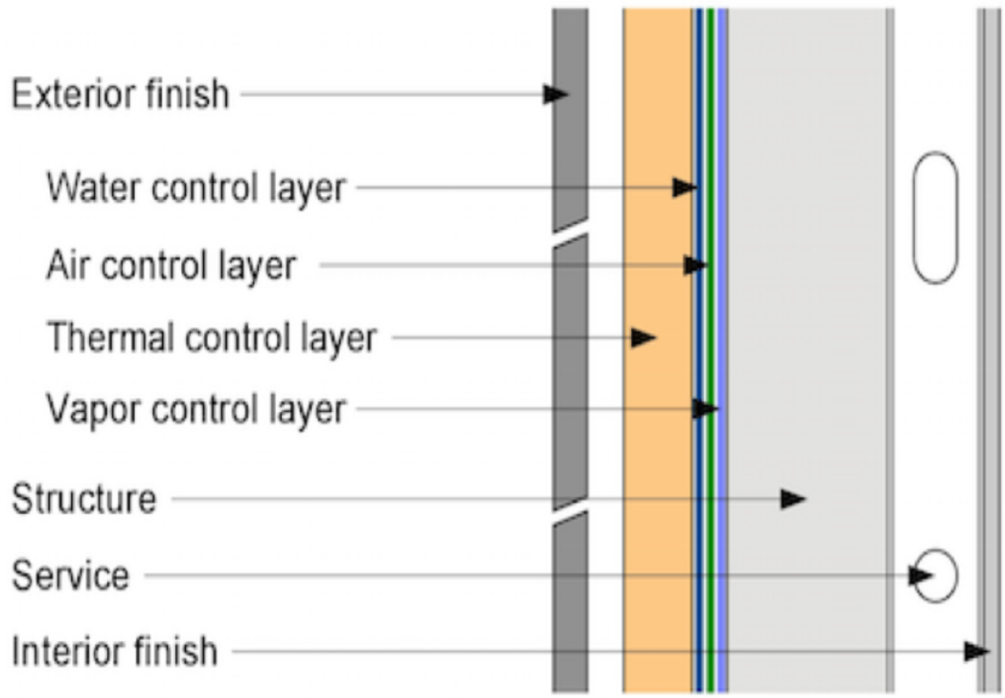


**Figure 4.1:** Layers of insulation in a perfect wall [37].

There are various layers of insulation which are used to maintain the indoor environment namely thermal, water, air, and vapor layers (as shown in Figure 4.1). Our primary focus deals with thermal performance and the others are added benefits. The insulation layers are sandwiched between the exterior finish which is the periphery of the buildings and the structure which is made of steel to form the frame of the walls. The service layer consists of the electrical and plumbing utilities fixed in a cemented wall placed just inside the interior layer made of material like plasterboards.

An insulation layer with a low value of thermal conductivity has better resistance to heat transfer. The other thermal properties of insulation materials are absorptivity, reflectivity, density, coefficient of thermal expansion, heat capacity and coefficient of thermal bridging [36].

- Absorptivity: It is defined as the ratio of absorbed radiation by a surface and is affected by the color of the surface. Black color has highest solar absorptance.
- Reflectivity: It is defined as the ratio of reflected radiation from a surface to total incident radiation on the surface.
- Density: It is the mass of material per unit volume.

- Thermal expansion coefficient: It is defined as the change in volume of a material due to change in temperature.
- Heat capacity: It is defined as the ability of the material to contain heat.
- Coefficient of thermal bridge: Thermal bridges are zones of a building envelope which has highest rate of heat transfer causing damage to structures and spread of molds and fungi. The coefficient of thermal bridge is the amount of heat transfer in the thermal bridges.

Research has proved that 60% of the heat losses occurs directly through the opaque structures of an enclosed with like walls and ceilings [36]. The remaining losses are due to glass windows, doors and infiltration through cracks and openings. Heat loss can occur either through conduction, convection, radiation, or a combination of all three as shown in Figure 4.2.

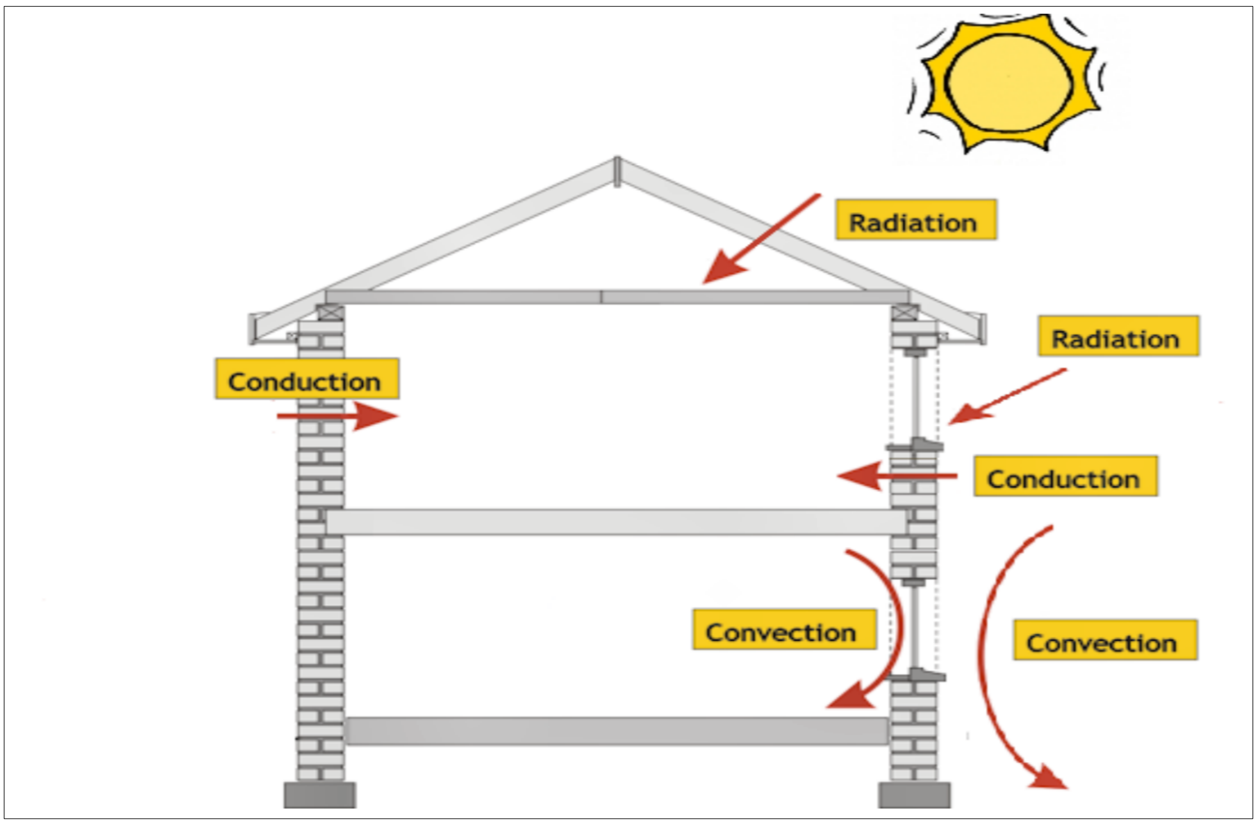


**Figure 4.2:** Modes of heat transfer through the building [36].

**4.2 Building Energy Modelling**

In this section, building energy is modelled using an open-source software, called EnergyPlus. This software was developed by the US Department of Energy (DOE) and is based on representing a rectangular house. Energy modelling help in scenario analysis and investigation of what if cases.

This would otherwise require a lot of resources like time and money. EnergyPlus is one such energy modelling software which saves a lot of resources and is used here to generate the energy model.

### 4.2.1 Shoebox Model

The shoebox model used in this study represents a basic rectangular house used as a basis of energy modelling in the EnergyPlus software. This simplified model optimizes the energy performance of buildings and help in making early decisions through informed choices.

The model, shown in Figure 4.3, represents a one-story building which is simulated for building energy performance in the city of Chicago (USA). The total building area is 48 $m^2$ and the height is 2.7 m with the whole house being air conditioned. This is a lightweight single-story construction without any interior partitions. It has two windows, one on either wall facing East and West directions.

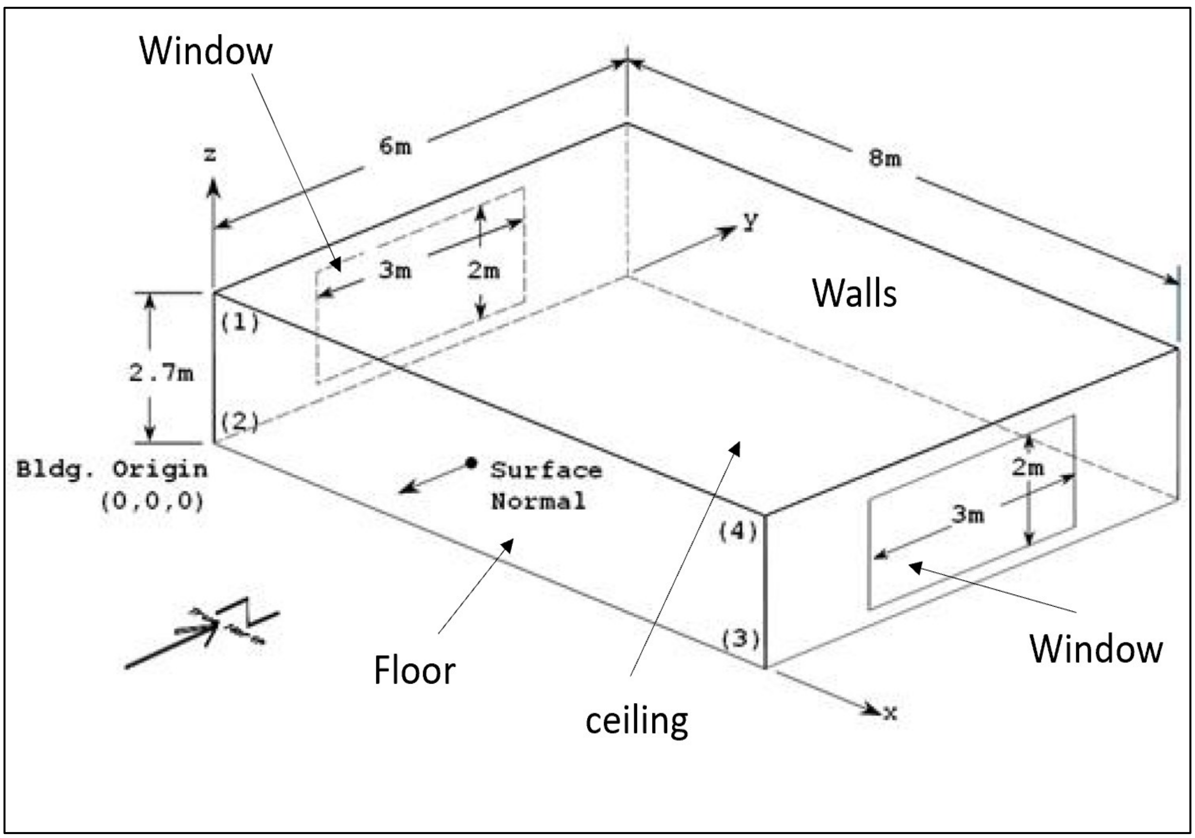


**Figure 4.3:** Shoebox model used for our analysis ahead in this paper using EnergyPlus software [38].

### 4.2.2 Area of the Walls of the Model

Area of the insulated walls = Area of the 4 walls – Area of the windows

$$= [(2 \times 6m \times 2.7m) + (2 \times 8m \times 2.7m)] – [2 \times 3m \times 2m]$$

$$= 75.6 \text{ m}^2 - 12 \text{ m}^2 = 63.6 \text{ m}^2$$

### 4.2.3 Built of the Walls

All the walls under consideration have the same built with 3 layers each. The outermost layer is made of wood siding which is 9 mm thick. The middle layer is the insulation region and by default the EnergyPlus software has a 66 mm thick Fiberglass quilt for the shoebox model on which we will carry out our simulations on. The innermost layer is made up of Plasterboard with a thickness of 12mm.

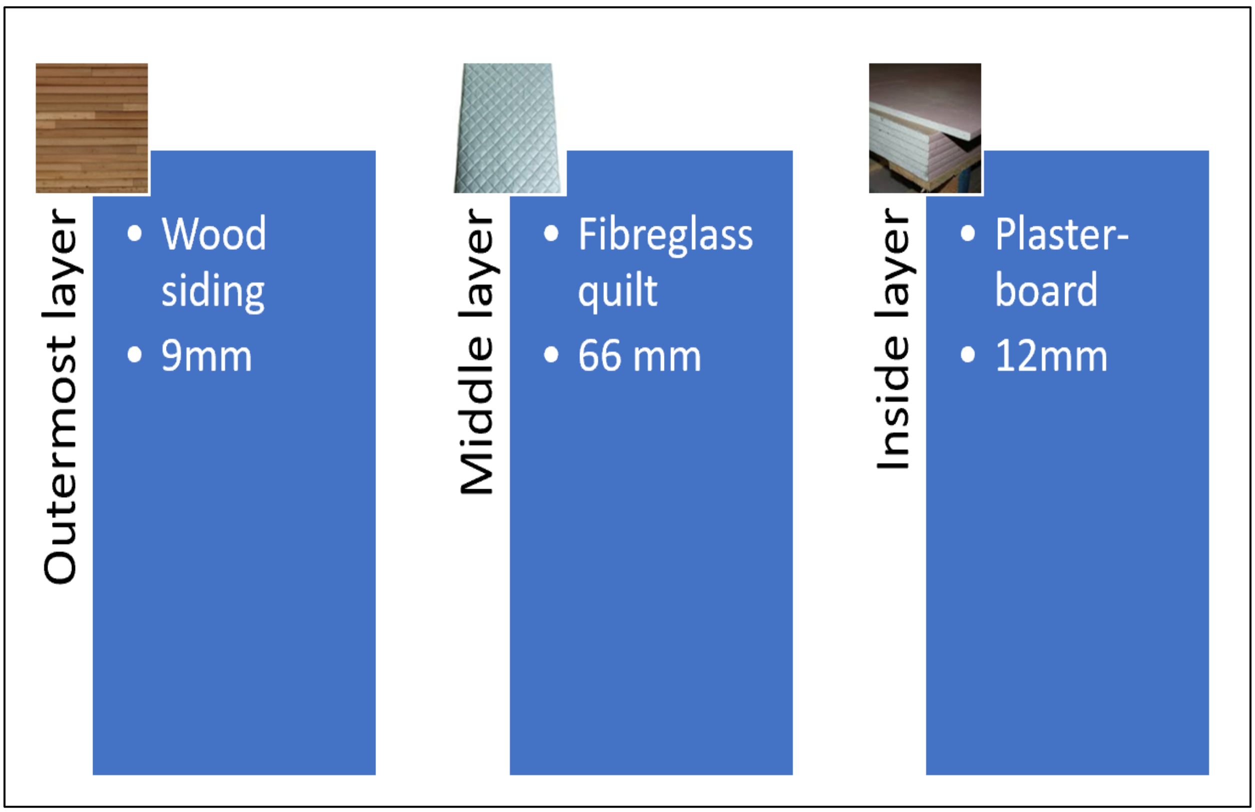


**Figure 4.4:** Built of the walls.

#### 4.2.4 Details of Surface Construction

Table 4.1 lists the materials used in the construction of walls, ceiling and floor along with the important properties like thermal conductivity, thickness, (U), thermal resistance (R), density and specific heat (C) needed for energy modelling using the shoebox model.

**Table 4.1:** Building construction materials used in energy modelling and their properties.

| Material (listed from outside to inside) | Conductivity (W/m-K) | Thickness (m) | U (W/m-K) | R (m-K/W) | Density (kg/m) | C (J/kg-K) |
|---|---|---|---|---|---|---|
| Walls | | | | | | |
| WOOD SIDING-1 | 0.140 | 0.009 | 15.556 | 0.064 | 530 | 900 |
| FIBERGLASS QUILT-1 | 0.040 | 0.066 | 0.606 | 1.650 | 12 | 840 |
| PLASTER-BOARD-1 | 0.160 | 0.012 | 13.333 | 0.075 | 950 | 840 |
| Roof | | | | | | |
| ROOF DECK | 0.140 | 0.019 | 7.368 | 0.136 | 530 | 900 |
| FIBERGLASS QUILT-2 | 0.040 | 0.066 | 0.606 | 1.650 | 12 | 840 |
| PLASTER-BOARD-2 | 0.160 | 0.010 | 1.60 | 0.625 | 950 | 840 |
| Floor | | | | | | |
| C5 CONCRETE | 1.73 | 0.1015 | 17.04 | 0.059 | 2243 | 837 |

#### 4.2.5 Establishing a Reference Case

One of the objectives of this research is the selection of the best insulation material. To achieve this objective, we will first establish a reference case with a default insulation material in the EnergyPlus software. Fiberglass is selected as the default insulation material in this study, since it is the most widely used insulation material in today's buildings. It is relatively inexpensive and its thermal performance remains unaffected by varying temperature profiles. It can be recycled by manufacturers and has decent dynamic stiffness.

Using fiberglass as the default insulation material in the shoebox model, it was determined that the total source energy per conditioned area is 1800.89 $MJ/m^2$ and the total site energy is 604.81

MJ/$m^2$. We are particularly interested in the total site energy since it gives the true picture of greenhouse gases released in the environment. The total site energy does not consider the total energy initially produced at source but only the amount used by the site. This does not account for energy losses during distribution or due to other factors. It should be kept in mind that energy lost is also a contributor to released emissions.

### 4.3 Insulation Materials

#### 4.3.1 Characteristics of Building Insulation Materials

Following characteristics of building insulation materials are considered in this study.

1. Thermal Conductivity: It is the passage of heat through an area of 1 $m^2$ and unit thick homogeneous material when there is a temperature gradient of $1^oK$. Units of thermal conductivity is W/m.K. This is one of the most important factors to determine the steady state thermal performance of a material. The lower the value of thermal conductivity, better is the heat insulation property of the material.

2. Density: It is mass per unit volume and the expressed in kg/$m^3$. It is useful to determine the thermal performance of a material in an unsteady state because it is used in the calculation to find thermal diffusivity.

3. Specific Heat: It is the ability or capacity of a material to accumulate or store a certain amount of heat. Its units are J/kg K. It is another factor to calculate thermal diffusivity of materials.

4. Water Vapor Diffusion Resistance: It is determined as the ratio of water vapor permeability of air (considered to be unity) to water vapor permeability of the material under study. It is a dimensionless quantity and generally speaking the higher its value, more difficult it is for water vapor to penetrate the surface of the material and thus, less possibility of formation of molds in between layers of walls.

5. Bending Stiffness: It is the resistance offered by a material to being deformed due to bending forces and measured in N.m. It depends on the Young's modulus of a material and the thickness of the insulation panel. Higher bending stiffness is desired for durability.

6. Functional Unit (fu) Weight: It is the weight of one functional unit of a material expressed in kg. One functional unit is expressed as the mass of the material required to obtain a thermal resistance of 1 $m^2$ K/W when the area of the specimen is fixed to be unity. It is one of the most important parameters used in the calculation of environmental impact of materials [39].

7. Embodied Energy: It is defined as the total amount of energy required to make a product assuming that all the energy used was incorporated inside it. It is expressed in Mj equivalent per functional unit. Broadly speaking, the embodied energy for synthetic materials are higher than natural ones [40].

8. Global Warming Potential (GWP): This factor is used to evaluate the effect of a material on global warming. It considers all the stages involved in the life cycle of a product from its creation to disposal and all the activities related to its transport or operation. It is expressed in units of kg $CO_{2eq}$ per fu [40].

9. Fire Classification: Insulation materials are categorized under various types depending upon the amount toxic smoke produced on burning, loss of mass and even increase in temperature of itself. It is a serious safety concern and toxic fumes are the culprits for casualty during fire related accidents.  The fire class specification is given in Table 4.2.

**Table 4.2:** Fire class ratings of materials [41].

| Fire class | Criteria |
|---|---|
| A1 | Temperature of material rises by a maximum of 30 degree Celsius and mass loss is less than 50%. There is no sustained flaming. It has absolutely no contribution to fire. |
| A2 | Temperature rises by maximum of 50 degree Celsius and mass loss is maximum of 50%. Arising flames may stay up to 20 seconds. It has limited combustibility and has no significant contribution to fire. |
| B | Total heat released is 7.5 Mega joules in 10 minutes and lateral flame can spread till the edge of the specimen. Flame can spread to 1.5 cm withing the first minute. Limited contribution to fire and combustible. |
| C | Total heat released is 15 Mega joules in 10 minutes and lateral flame can spread till the edge of the specimen. Flame can spread to 1.5 cm withing the first minute. Burning intensity is 250 Watts per second. Minor contribution to fire and combustible. |
| D | Flame can spread to 1.5 cm withing the first minute. Burning intensity is 750 Watts per second. Medium contribution to fire and combustible. |
| E | Flame can spread to 1.5 cm within the first 20 seconds. It will also produce burning droplets which can create huge fire if it is complemented by slight wind. Contributes highly to fire and combustible. |
| F | It is easily flammable and combustible |

10. Cost: It is one of the triple bottom lines of companies. It has no direct contribution to the environment, but the cost mechanism can promote eco-friendly materials by subsidies and discounts. For our purpose, we have found the cost of insulation materials per $ft^2$ with R-value of 1 $m^2K/W$. The unit is in Dollars ($).

### 4.3.2 Characteristics of Fiberglass Insulation

Table 4.3 lists the properties of fiberglass insulation.

**Table 4.3:** Properties of fiberglass insulation.

| Characteristic | Value | References |
|---|---|---|
| Thermal Conductivity (W/mK) | 0.04 | 42,43 |
| Density (kg/m$^3$) | 12 | 44 |
| Specific Heat Capacity (kJ/kgK) | 0.84 | 44 |
| Water Vapor diffusion resistance factor | 1.05 | 45 |
| Bending Stiffness (Nm) | 4.88459E-05 | 46 |
| fu weight (kg) | 8 | 42,43 |
| Embodied energy (per fu) | 229.02 | 42,43 |
| Global Warming Potential (GWP) (per f.u) | 9.89 | 42,43 |
| Fire classification | A1-A2 | 47 |
| Cost per square foot per R-value | $0.02 | 48 |

### 4.3.3 Comparison of Fiberglass with Other Insulation Materials

Fiberglass is one of the most popular insulation materials due to various properties although it might not be one of the best choices when we scrutinize it under various attributes. Ultimately it is the decision of the engineer to select which properties he or she wish to emphasize over, to serve the purpose of the buildings.

We have established a reference case of energy consumption for our shoebox model with Fiberglass being used for insulation. Now, we will model with other insulation materials to make a comparison. For this, we first need to calculate the heat loss in our shoebox model. Steps to find heat loss through walls are shown below [49].

$$Daily\ Total\ Heat\ loss\ for\ heating\ season = \frac{Area\ X\ HDD\ X\ 24}{R{-}value\ X\ 5.67826} \tag{4.1}$$

In Equation (4.1), the total heat loss through the surface area of walls is measured in British Thermal Units (BTU), Area is in square feet, HDD stands for Heating Degree Day, which for the city of Chicago is 6339 and the R-value signifies the potential to resist flow of heat [50]. Sometimes a unit called apparent R-value is used to combine heat losses due to conduction, convection, and heat losses. A factor of 5.67826 is multiplied in the denominator to convert R-value from SI units to inch-pound system. In our calculation we have used the following formula:

$$R - value = \frac{Thickness\ of\ material}{Thermal\ conductivity} \qquad (4.2)$$

For our shoebox model, we have 3 layers of materials and the total R-value will be summation of individual R-values, which as shown in Table 4.4, is 1.789 $m^2K/W$.

**Table 4.4:** R-value of walls of shoebox model.

| Layer | Thermal Conductivity (W/m.K) | Thickness (m) | R- value ($m^2K/W$) | R-value of wall ($m^2K/W$) |
|---|---|---|---|---|
| Wood siding | 0.14 | 0.009 | 0.064 | |
| Fiberglass | 0.04 | 0.066 | 1.65 | 1.789 |
| Plasterboard | 0.16 | 0.012 | 0.075 | |

- For determining the energy loss using Equation (4.1), we will use the data provided by EnergyPlus software for Fiberglass.
- $Total\ Heat\ loss\ for\ heating\ season = \frac{684.5874\ X\ 6339\ X\ 24}{1.789\ X\ 5.67826}$

$$= 10{,}252{,}629.89\ BTU$$

Once the energy loss from the formula is found out, we back substitute the values of energy loss to find thickness of insulation materials to find the exact value of GWP, Embodied Energy and bending stiffness as these are the parameters which depend on the mass of materials. To find out the mass of the material, it is important to find the thickness and density of the material. The latter is obtained from manufacturer's brochure and literature reviews while the former is calculated from the R-values. Once the total heat loss is fixed, we can use Equation (4.1) to obtain thickness of various insulation materials by back substitution.

### 4.4 Alternative Insulation Materials

Following alternative insulation materials are considered in this study.

1. Stone wool: It is a conventional insulation material formed by melting rocks and bound using oils and resins. They are characterized by good sound absorbing properties and can be recycled by manufacturers or disposed in landfills [51].
2. Expanded Polystyrene (EPS): It is a rigid and white colored conventional material made from evaporation of pentane mixed in polystyrene grains. EPS has poor acoustic and fire-resistant properties and releases toxic fumes on catching fire. It is recycled but only by specialized industries. It is a conventional insulation material [51].
3. Polyurethane (PUR): Produced in the form of foam through an exothermic reaction between its constituting compounds, PUR is a conventional insulation material. Their acoustic and fire-resistant properties are like EPS. The recycling of these materials demands specialized industries [51].
4. Polyisocyanurate (PIR): Process of formation is like PUR and the result is a foam plastic. The fire class is B which represents better resistance to fire and less emission of fumes. Like PUR and EPS, PIR also demands specialized industries to recycle foam plastic at the end of useful life like some of the other conventional insulation materials [51].
5. Hemp Fiber: It is a natural fiber obtained from an herbaceous plant and originating from Eastern Asia, hemp fibers are preferred because of their good biodegradable properties and consequent better end of life treatability. Their thermal conductivity increases with absorption of moisture and they need isolation from rodents, insects, and water [51].
6. Kenaf: Kenaf is obtained from Hibiscus Cannabinus which is a fast-growing plant native to Southern Asia. Unlike hemp it is not an attractive option for pests because Kenaf plant is devoid of any protein. The bending stiffness of this material is low. For Kenaf to be a viable natural fiber it should be cultivated near its processing plants and the end of life phase must include energy recovery schemes so that impact to the environment is limited [51].
7. Flax: It is a natural fiber made of 70% cellulose and has been used since centuries. It is manufactured in rolls and its ability to hold air, lends it good insulating property. Studies

have shown that they have good acoustic thermal performance. Easy end of life recycling and compost production makes it an appealing alternative [51].

8. Sheep Wool: Obtained from sheep, this natural fiber is manufactured in rolls. Although marked by good insulation performance in winters, it can be unsteady in hotter temperatures. Its ability to absorb moisture and easy end of life disposal phase makes it a good choice of insulation material [51].

9. Coir Fiber: Obtained from the husk of coconuts, this natural fiber is a mere byproduct of the coconut industry. It is one of the most promising fibers on the list due to high mechanical strength, remains unaffected by rodents and insects, and fire- retardant properties can be easily added. The only major drawback is energy consumed in transportation because it is mainly available in the regions surrounding, India, Sri Lanka and Indonesia [51].

10. Jute Fiber: Jute fiber is obtained from Jute plant which is mainly grown in India and Bangladesh. The drawback of jute is like Coconut fiber but more pronounced in terms of transportation impacting the environment. It has decent thermal properties but is offset by a low density [51].

Properties of the alternative insulation materials are listed in Table 4.5. The table shows that some of the materials perform well on some aspect while others do well in the remaining aspects. To determine which property is significant and by how much the need for assigning priority occurs and this involves decision making. There are various characteristics or attributes and various insulation materials under scrutiny. This will involve a Multi-Criteria Decision-Making tool. Analytical Hierarchical Process is one such tool which has been widely used across industries. But before we go to the decision-making process, we need to determine the thickness, embodied energy and GWP of all alternative materials.

.

**Table 4.5:** Properties of alternative insulation materials.

| Material | Thermal Conductivity (W/mK) | Density (Kg/m$^3$) | Specific Heat Capacity Kj/kg k | Water Vapour diffusion resistance factor | f.u. weight (kg) | Embodied energy of 1 F.U. (kg) | GWP per f.u. (kg $CO_2$ eq) | Fire classification | Bending Moment (Nm) | Cost per ft$^2$ per R-value ($) |
|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 0.0365 | 120 | 0.9 | 1.15 | 1.18 | 20.75 | 1.45 | A1-A2-B | 5.05356E-06 | 0.03 |
| Expanded Polystyrene | 0.0345 | 25 | 1.25 | 45 | 0.8 | 127.31 | 5.05 | E | 1.3842E-05 | 0.07 |
| Polyurethane | 0.031 | 30 | 1.375 | 100 | 0.96 | 99.63 | 6.51 | E | 3.0316E-06 | 0.02 |
| Polyisocyanurate | 0.023 | 37.5 | 1.45 | 102.5 | 0.68 | 215 | 4.29 | B | 1.23814E-06 | 0.1 |
| Hemp Fibre | 0.049 | 55 | 1.65 | 1.5 | 1.55 | 29.6 | 0.43 | E | 2.16997E-05 | 0.09 |
| Kenaf | 0.0385 | 105 | 1.65 | 1.75 | 1.52 | 59.37 | 3.17 | D-E | 1.01626E-05 | 0.08 |
| Flax | 0.0565 | 60 | 1.5 | 1.5 | 1.26 | 49.73 | 1.1 | E | 3.44139E-05 | 0.6 |
| Sheep Wool | 0.046 | 17.5 | 1.5 | 2 | 0.76 | 17.12 | 1.46 | E | 1.7953E-05 | 0.05 |
| Coir Fiber | 0.0425 | 100 | 1.45 | 17.5 | 9 | 14.75 | 0.55 | D-E | 1.4159E-05 | 0.14 |
| Jute Fiber | 0.0465 | 67.5 | 2.3 | 1.5 | 5 | 105.54 | 2.79 | E | 1.79054E-05 | 0.49 |
| Fiberglass | 0.04 | 45 | 0.84 | 1.05 | 8 | 229.02 | 9.89 | A1-A2 | 4.88459E-05 | 0.02 |

### 4.5 Thickness of Alternative Insulation Materials.

The thickness of an insulation material depends upon its thermal conductivity and the climate of the region where it is used. For a place where high heating needs are demanded, materials with low thermal conductivity will have lower thickness as compared to materials with high thermal conductivity. The increase in thickness consequently has bearings on other factors, such as GWP, embodied energy and bending stiffness. Thus, it becomes important to find the thickness of materials being considered for selection.

For the shoebox model used, the default material was fiberglass and the total heat requirement of the model for the season was calculated to be 10,252,629.89 BTU. For the alternative insulation material to give same amount of heat loss, the R value must remain the same, but since their thermal conductivity is different from that of the fiberglass thickness, their thickness will be different. Using the thickness of fiberglass as 0.066 meters (which was determined using the shoebox model) and thermal conductivity to be 0.04 W/mK in Eqaution (4.2), its R-value is calculated as 1.65. The thickness of the alternative materials to obtain the same R-value is then back calculated using Equation (4.2). The thickness values are listed in Table 4.6.

**Table 4.6:** Calculation of thickness of alternative insulation materials.

| Material | Thermal Conductivity | Desired R value | Required thickness (ft) | Required thickness (m) |
|---|---|---|---|---|
| Stone Wool | 0.0365 | 1.65 | 0.060225 | 0.01835658 |
| Expanded Polystyrene | 0.0345 | 1.65 | 0.056925 | 0.01735074 |
| Polyurethane | 0.031 | 1.65 | 0.05115 | 0.01559052 |
| Polyisocyanurate | 0.023 | 1.65 | 0.03795 | 0.01156716 |
| Hemp Fiber | 0.049 | 1.65 | 0.08085 | 0.02464308 |
| Kenaf | 0.0385 | 1.65 | 0.063525 | 0.01936242 |
| Flax | 0.0565 | 1.65 | 0.093225 | 0.02841498 |
| Sheep Wool | 0.046 | 1.65 | 0.0759 | 0.02313432 |
| Coir Fiber | 0.0425 | 1.65 | 0.070125 | 0.0213741 |
| Jute Fiber | 0.0465 | 1.65 | 0.076725 | 0.02338578 |
| Fiberglass | 0.04 | 1.65 | 0.066 | 0.0201168 |

### 4.6 Global Warming Potential (GWP).

Using the table and steps below we will find the total GWP for our model.

**Table 4.7:** Key for column numbers used in calculation of total GWP in Table 4.8.

| Column No | Name of column |
|---|---|
| 1 | Material |
| 2 | Thermal Conductivity (W/mK) |
| 3 | R value ($m^2$ k/W) for calculation of F.U. |
| 4 | Thickness L (in m) of F.U. |
| 5 | Mass of 1 F.U. (kg) |
| 6 | Simulated thickness (m) |
| 7 | Density (Kg/$m^3$) |
| 8 | volume ($m^3$) |
| 9 | Mass of substance used in envelope (kg) |
| 10 | Effective F.U.s |
| 11 | GWP per f.u. (kg $CO_2$ eq) |
| 12 | Total GWP (kg $CO_2$ eq) |

**Step 1: Calculation of mass of material used for our model.**

Mass = volume x density of insulation material

Volume = area x simulated thickness, Area = 63.6 $m^2$

Column 9 gives the total mass in kgs for the materials used in different cases.

**Step 2: Calculation for effective functional units (f.u.)**

Functional units are weight of substance that are needed to obtain an R value of 1 $m^2$ K/W for an area of 1 meter square.

$$\text{Effective f.u.} = \frac{Toatl\ mass\ of\ substance\ in\ the\ model}{Mass\ of\ 1\ Functional\ Unit} \qquad (4.3)$$

Column 10 gives the effective f.u. for the materials used in different cases.

**Step 3: Calculation for GWP for the amount of insulation material used in the model**

$$\text{Total GWP of material} = \text{GWP of 1 f.u. x Effective f.u.} \quad (4.4)$$

Column 12 gives the total GWP for the materials used in different cases.

**Table 4.8:** Total GWP for the model.

| Material | Thermal Conductivity (W/mK) | R value (m2 k/W) for calculation of F.U. | Thickness L (in m) of F.U. | Mass of 1 F.U. (kg) | Simulated thickness (m) | Density (Kg/m3) | volume (m3) | Mass of substance used in envelope (kg) | Effective F.U.s | GWP per f.u. (kg CO2 eq) | Total GWP (kg CO2 eq) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 0.0365 | 1 | 0.0365 | 1.18 | 0.01835658 | 120 | 0.01835658 | 140.0974186 | 118.7266259 | 1.45 | 172.1536076 |
| Expanded Polystyrene | 0.0345 | 1 | 0.0345 | 0.8 | 0.01735074 | 25 | 0.01735074 | 27.5876766 | 34.48459575 | 5.05 | 174.1472085 |
| Polyurethane | 0.031 | 1 | 0.031 | 0.96 | 0.01559052 | 30 | 0.01559052 | 29.74671216 | 30.9861585 | 6.51 | 201.7198918 |
| Polyisocyanurate | 0.023 | 1 | 0.023 | 0.68 | 0.01156716 | 37.5 | 0.01156716 | 27.5876766 | 40.57011265 | 4.29 | 174.0457833 |
| Hemp Fibre | 0.049 | 1 | 0.049 | 1.55 | 0.02464308 | 55 | 0.02464308 | 86.20149384 | 55.61386699 | 0.215 | 11.9569814 |
| Kenaf | 0.0385 | 1 | 0.0385 | 1.52 | 0.01936242 | 105 | 0.01936242 | 129.3022408 | 85.06726366 | 3.17 | 269.6632258 |
| Flax | 0.0565 | 1 | 0.0565 | 1.26 | 0.02841498 | 60 | 0.02841498 | 108.4315637 | 86.05679657 | 1.1 | 94.66247623 |
| Sheep Wool | 0.046 | 1 | 0.046 | 0.76 | 0.02313432 | 17.5 | 0.02313432 | 25.74849816 | 33.87960284 | 1.46 | 49.46422015 |
| Coir Fiber | 0.0425 | 1 | 0.0425 | 9 | 0.0213741 | 100 | 0.0213741 | 135.939276 | 15.104364 | 0.55 | 8.3074002 |
| Jute Fiber | 0.0465 | 1 | 0.0465 | 5 | 0.02338578 | 67.5 | 0.02338578 | 100.3951535 | 20.07903071 | 2.79 | 56.02049568 |
| Fiberglass | 0.04 | 1 | 0.04 | 8 | 0.0201168 | 45 | 0.0201168 | 57.5742816 | 7.1967852 | 9.89 | 71.17620563 |

### 4.7 Embodied Energy

Using the Table 4.9 and steps below, we will find the total Embodied energy for our model.

**Table 4.9:** Key for column numbers used in calculation of Total Embodied Energy in Table 4.10.

| Column No | Name of column |
|---|---|
| 1 | Material |
| 2 | Thermal Conductivity (W/mK) |
| 3 | R value ($m^2$ k/W) for calculation of F.U. |
| 4 | Thickness L (in m) of F.U. |
| 5 | Mass of 1 F.U. (kg) |
| 6 | Simulated thickness (m) |
| 7 | Density (Kg/$m^3$) |
| 8 | volume ($m^3$) |
| 9 | Mass of substance used in envelope (kg) |
| 10 | Effective F.U.s |
| 11 | Embodied energy of 1 F.U. (kg) |
| 12 | Total Embodied energy of material ($Mj_{eq}$) |

**Table 4.10:** Total Embodied Energy for the model.

| Material | Thermal Conductivity (W/mK) | R value ($m^2$ k/W) for calculation of F.U. | Thickness L (in m) of F.U. | Mass of 1 F.U. (kg) | Simulated thickness (m) | Density (Kg/$m^3$) | volume ($m^3$) | Mass of substance used in envelope (kg) | Effective F.U.s | Embodied energy of 1 F.U. (kg) | Total Embodied energy of material (Mjeq) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 0.0365 | 1 | 0.0365 | 1.18 | 0.01835658 | 120 | 0.01835658 | 140.0974186 | 118.7266259 | 20.75 | 2463.577487 |
| Expanded Polystyrene | 0.0345 | 1 | 0.0345 | 0.8 | 0.01735074 | 25 | 0.01735074 | 27.5876766 | 34.48459575 | 127.31 | 4390.233885 |
| Polyurethane | 0.031 | 1 | 0.031 | 0.96 | 0.01559052 | 30 | 0.01559052 | 29.74671216 | 30.9861585 | 99.63 | 3087.150971 |
| Polyisocyanurate | 0.023 | 1 | 0.023 | 0.68 | 0.01156716 | 37.5 | 0.01156716 | 27.5876766 | 40.57011265 | 215 | 8722.574219 |
| Hemp Fibre | 0.049 | 1 | 0.049 | 1.55 | 0.02464308 | 55 | 0.02464308 | 86.20149384 | 55.61386699 | 29.6 | 1646.170463 |
| Kenaf | 0.0385 | 1 | 0.0385 | 1.52 | 0.01936242 | 105 | 0.01936242 | 129.3022408 | 85.06726366 | 59.37 | 5050.443443 |
| Flax | 0.0565 | 1 | 0.0565 | 1.26 | 0.02841498 | 60 | 0.02841498 | 108.4315637 | 86.05679657 | 49.73 | 4279.604493 |
| Sheep Wool | 0.046 | 1 | 0.046 | 0.76 | 0.02313432 | 17.5 | 0.02313432 | 25.74849816 | 33.87960284 | 17.12 | 580.0188007 |
| Coir Fiber | 0.0425 | 1 | 0.0425 | 9 | 0.0213741 | 100 | 0.0213741 | 135.939276 | 15.104364 | 14.75 | 222.789369 |
| Jute Fiber | 0.0465 | 1 | 0.0465 | 5 | 0.02338578 | 67.5 | 0.02338578 | 100.3951535 | 20.07903071 | 105.54 | 2119.140901 |
| Fiberglass | 0.04 | 1 | 0.04 | 8 | 0.0201168 | 45 | 0.0201168 | 57.5742816 | 7.1967852 | 229.02 | 1648.207747 |

### 4.8 Decision Making

Decision making requires gathering information and assessing all possible solutions with the constraint of time and cost. There are various elements of decision making. It comprises of understanding and identifying the objective of the decision and the impact of making the decision. For this to happen, it is better to process as much data possible provided there are sufficient resources. Then alternatives are identified and weighed. The weights and performance of alternatives enables the decision maker to take the appropriate action and analyze the consequences before declaring the final decision [52].

Analytical Hierarchal Process is one decision making tool which this study has identified could be best suited for taking the decision. It is discussed in detail in the next sections.

#### 4.8.1 Analytical Hierarchical Process (AHP)

AHP was developed by Saaty in 1970s and has been modified several times over the years. It uses a combination of mathematics and instincts of the decision-maker to compare two unlike quantities (like cost and embodied energy). The objective of the decision is established first followed by determining the contribution of attributes and alternatives. This is done by performing pairwise comparisons, the core of AHP. A rating scale is utilized to find weights of individual attributes and alternatives. We have modified this scale and explained it in the following sections.

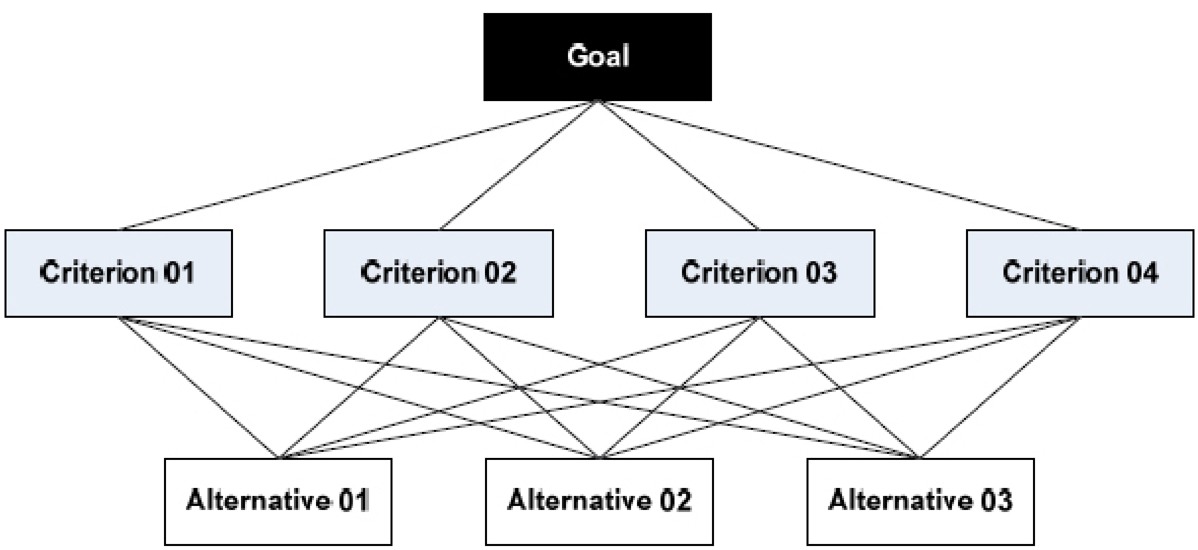


**Figure 4.5:** AHP process [53].

### 4.8.2 Rating Scale

The traditional rating scale for AHP is shown below.

| Level of Importance | Definition | Interpretation |
|---|---|---|
| 1 | Equally preferred | Two activities contribute equally to the objective |
| 3 | Moderately | Experience and judgment slightly favour one activity over another |
| 5 | Strongly | Experience and judgment strongly or essentially favour one activity over another |
| 7 | Very strongly | An activity is strongly favoured over another and its dominance demonstrated in practice |
| 9 | Extremely | The evidence favouring one activity over another is of the highest degree possible for affirmation |
| 2, 4, 6, 8, ... | Intermediate values | Used to represent a compromise between preferences listed above |

**Figure 4.6:** Traditional rating scale for AHP [54].

### 4.8.3 Modified AHP

The traditional AHP method relies dominantly on the pairwise comparison of attributes. An attribute which is highly preferred influences the final decision more when compared to the other attributes. But the widely used rating scale in this process poses a question. A rigid scale of level of importance ranging from 1 to 9 is used. Attributes are pitted against each other on this scale which yields a very generalized picture. These decisions and comparisons are done from the instincts of the decision-maker. It is possible that the consistency of the comparison between the attributes is not correct. Consider for example, attribute A dominates B and attribute B dominates C. But the decision-maker, while rating A against C can rate C marginally higher than A. This violates the consistency of judgements. In our modified AHP, we first determine which attribute is the most important and by how much, and then form a ranked order.

Another aspect which raises question in traditional AHP is that way attributes are compared against each other under various attributes. A generalized 1 to 9 scale is used. In our modification, instead of the traditional scale, a ratio of scaled weights is taken which requires an additional step.

In this step just before pairwise comparison of alternatives, each alternative is quantified under all attributes. So, we have a ranked performance order of all alternatives under all attributes. At the end of this step, the best performing alternate gets a value of 100 and this is used to determine the scaled weight of other alternatives. While doing the pairwise comparison, we simply take the ratio of scaled weights.

### 4.8.4 Advantages of the Modified AHP

There are three advantages which arise due to the modifications mentioned above:

- Consistent judgement of importance of attributes.

The attributes are carefully studied and the impact of each attribute to the final decision yields its order of priority. Thus, there is a clear distinction between more important attributes and the lesser ones which the decision-maker has prioritized.

- Quantified values of performance of alternatives under various attributes.

The alternatives are weighted from 0 to 100 and then a scaled weight is calculated. Thus, we find a way to compare the tangible and qualitative characteristics (like fire classification) properties.

- Dependence on reliable data rather than instinctive values.

Once the scaled weights are established in our modified AHP, these values are used in pairwise comparison. In the traditional AHP, reliability is on the expertise in judgement of decision-maker which is not sound when compared to our modification. Scaled weight gives us a logic for comparing alternatives rather than pure expert instincts.

### 4.8.5 Modified Rating Scale for Pairwise Comparison of Attributes

The scale developed for pairwise comparison of attributes is shown in Table 4.11.

**Table 4.11:** Modified rating scale for pairwise comparison of attributes.

| Level of importance | Definition | Interpretation |
|---|---|---|
| 0.9 | Extremely preferred | Evidently influences final decision more than any other value |
| 0.7 | Strongly preferred | Strongly influences the objective and essentially favors one attribute over another |
| 0.5 | Equally preferred | Both contribute equally to objective |
| 0.3 | Strongly less preferred | Has a very low influence on the objective when compared to the attribute it is compared against |
| 0.1 | Extremely less preferred | The influence on the final decision will be negligent when compared to the attribute it is compared against |
| Intermediate values | A compromise between the high and low values | It represents impact on objective with effects intermediate in between the adjoining values |

Attributes are compared against each other and then a fractional value is assigned to the two attributes under head-to-head comparison. In the image below, Attribute A is given a value of 0.9 because it is highly preferred over Attribute B which has an assigned value of 0.1. It can also be noted that the two values when summed up gives a value equal to 1.

**Table 4.12:** Illustration to represent modified rating scale.

| Attribute | A | B |
|---|---|---|
| A | 1 | 0.9 |
| B | 0.1 | 1 |

The inference of the table yields that Attribute A is extremely preferred over Attribute B. The influence of A over B would be extremely more preferred in the final decision.

### 4.8.6 Rating Scale to Determine Scaled Weight of Alternatives

In the traditional AHP method where alternatives are compared on a scale of 1 to 9, in the modified approach there is no such scale. Instead, a scale is used to normalize the performance of alternatives under various attributes and then scaled weight is calculated. Later the ratio of scaled weights is used for pairwise comparison.

The rating scale in Table 4.13 represents the performance of various materials under different attributes.

**Table 4.13:** Rating scale to determine scaled weight of alternatives.

| Level of importance | Definition | Interpretation |
|---|---|---|
| 100 | Best case | Evidently influences final decision more than any other value |
| 70 | Good performance | Strongly influences the objective and essentially favors one attribute over another |
| 50 | Decent performance | Has reasonable impact on the final decision |
| 30 | Below average performance | Has low impact on the objective |
| 10 | Poor performance | The influence will be least on the objective |
| Intermediate values | A compromise between the high and low value | It represents impact on objective with effects intermediate in between the adjoining values |

## 4.9 Shortlisted Attributes

Here is a list of attributes or characteristics which dominate the priorities in decision making when insulation materials are selected.

- Global Warming Potential (GWP)

- Embodied Energy
- Bending Stiffness
- Water Vapor Diffusion Resistance Factor
- Thermal Conductivity
- Cost
- Fire Classification

**4.10 Determining Priority of Attributes**

The comparison of attributes in the section below represents the weight of attributes with respect to GWP. We will see in the next paragraph why GWP gains highest priority. Once we establish the relation between GWP and other attributes, we can then relate attributes with each other. This will yield the weight of characteristics in the decision matrix. The pairwise comparison between attributes is done on a scale of 0 to 1. The attribute with higher priority will have the higher value and the amount by which it is higher would reflect how important one characteristic is over the other.

- **GWP and Embodied Energy:** The motivation guiding this thesis is investigation of reasons for emissions of greenhouse gases and ways to curb them. GWP and embodied energy are key indicators to emissions because both relate to energy in the various life cycle of products. So, the aforementioned factors are assigned highest priority. GWP looks at energy usage in all life cycle phases of a product and considers the source of energy. If renewable sources of energy are used, then embodied carbon is less. GWP evaluates for carbon sequestration and end of life reuse, recycle, or disposal stage. Embodied Energy on the other hand does not consider the end-of-life stage. Thus, a better picture is served by GWP. Nevertheless, Embodied Energy has been widely used in the industries and promising data for study is available [40].

For our purpose we assume that GWP is better rated than Embodied Energy but only slightly.

Relative weight: GWP = 0.60; Embodied Energy = 0.40

- **Bending stiffness, WVDRF, Thermal conductivity:** Bending stiffness is the factor which will decide how much force an insulation member can withstand before becoming out of shape [55]. The expected life of insulation panels is expected to be well over 50 years thus, having a good value for bending stiffness becomes essential. A disfigured panel means leakages, impacting the need for more heating or cooling, translating to more emissions. Thus, after GWP and Embodied Energy, Bending Stiffness is the factor which is responsible for most emissions and is given the next priority. It is followed by WVDRF which can cause creation of fungus in the layers of insulation [51]. Installing a new panel would mean addition of more embodied energy to the building thus leading to more emissions. Although WVDRF is not a direct contributor to emissions, it encourages it indirectly. After WVDRF, next in priority is thermal conductivity. To attain a desired amount of heat loss we fix the R value of the walls. A low value of thermal conductivity is easily compensated by increasing the thickness of materials. This increases the cost of material and embodied carbon, but the tradeoff between energy saved and embodied carbon or cost still yields positive result for increased thickness.

We represent the relative weight of attributes with respect to GWP below:

Relative weight: GWP = 0.7; Bending Stiffness = 0.30

Relative weight: GWP = 0.75; WVDRF = 0.25

Relative weight: GWP = 0.8; Thermal conductivity = 0.20

- **Cost and Fire classification:** Cost is one of the triple bottom lines of companies. This does not directly impact emissions. But factors like WVDRF, Bending Stiffness and Thermal conductivity are more important because they effect the embodied carbon. Cost comes above fire rating because, fire accidents are not commonplace. They are one off events and improved engineering further reduces the need for weightage to fire events. Instead, the money saved on investing in fire events can be used in other emission reducing things like carbon capture or LEDs.

We represent the relative weight of attributes with respect to GWP below:

Relative weight: GWP = 0.85; Cost = 0.15

Relative weight: GWP = 0.90;      Fire classification = 0.1

### 4.11 Priority of Attributes

The analysis of attributes above shows that GWP is the most important attribute being considered followed by Embodied Energy and Bending stiffness. By assigning priority to the attributes, we make the consistency of the assignment of weights to these attributes more reliable. Table 4.14 shows the order of the ranks of these attributes. Later, the AHP method will yield by how much one attribute dominates the other in the final decision of selection of best insulation material.

**Table 4.14:** Priority of attributes.

| Attribute | Rank |
|---|---|
| GWP | 1 |
| Embodied Energy | 2 |
| Bending stiffness | 3 |
| WVDRF | 4 |
| Thermal Conductivity | 5 |
| Cost | 6 |
| Fire Classification | 7 |

## 4.12 Steps Involved in Performing AHP

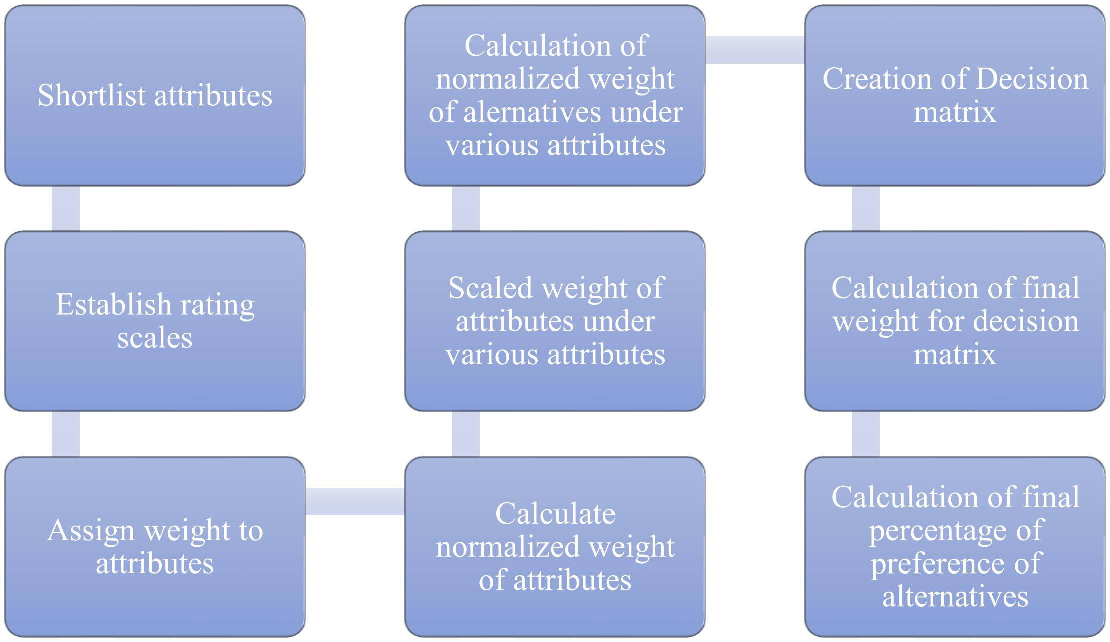


**Figure 4.7:** Flowchart for process of AHP.

**Step 1: Shortlist attributes and alternatives**

Please refer to section 4.8 for attributes and section 4.3 for alternatives.

**Step 2: Establish rating scale.**

Refer to Table 4.11 and 4.13 for modified rating scales discussed earlier.

**Step 3: Assigning weights to attributes.**

Attributes are compared against each other and then a fractional value of 1.0 is assigned to the two attributes under head-to-head comparison. In the Table 4.15 (shown below), GWP is given a value of 0.9 (in 2$^{nd}$ row; last column) because it is highly preferred over fire classification rating which has an assigned value of 0.1. It can also be noted that the two values when summed up gives a value equal to 1.

**Table 4.15:** A fractional value of 1 is assigned for head-to-head comparison of attributes.

| Attributes | GWP | Embodied Energy | Bending stiffness | WVDRF | Thermal conductivity | Cost | Fire Class |
|---|---|---|---|---|---|---|---|
| GWP | 1 | 0.6 | 0.7 | 0.75 | 0.8 | 0.85 | 0.9 |
| Embodied Energy | 0.4 | 1 | 0.65 | 0.7 | 0.75 | 0.8 | 0.85 |
| Bending stiffness | 0.3 | 0.35 | 1 | 0.55 | 0.7 | 0.75 | 0.8 |
| WVDRF | 0.25 | 0.3 | 0.45 | 1 | 0.65 | 0.7 | 0.75 |
| Thermal conductivity | 0.2 | 0.25 | 0.3 | 0.35 | 1 | 0.6 | 0.65 |
| Cost | 0.15 | 0.2 | 0.25 | 0.3 | 0.4 | 1 | 0.6 |
| Fire Class | 0.1 | 0.15 | 0.2 | 0.25 | 0.35 | 0.4 | 1 |

**Step 4: Calculation of normalized weight of attributes**

- First, we find the product of all the values in the row corresponding to the attribute.
- Next, we calculate Geometric mean of each row product given by:

  GM = (Row Product)$^{(1/n)}$, where n = no of attributes (7 for our analysis)
- Next, we sum all the geometric means to find normalized weight.
- To calculate the normalized weight, we divide the GM of each attribute by the sum of GMs.

**Table 4.16:** Table for calculation of normalized weight of attributes (in the table the sum of GM = 3.64328108).

| Attributes | GWP | Embodied Energy | Bending stiffness | WVDRF | Thermal conductivity | Cost | Fire Class | Row Product | Geometric Mean | Sum of GM | Normalized weights |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GWP | 1 | 0.6 | 0.7 | 0.75 | 0.8 | 0.85 | 0.9 | 0.19278 | 0.7904347 | 3.64328108 | 0.21695683 |
| Embodied Energy | 0.4 | 1 | 0.65 | 0.7 | 0.75 | 0.8 | 0.85 | 0.09282 | 0.71206596 | 3.64328108 | 0.19544634 |
| Bending stiffness | 0.3 | 0.35 | 1 | 0.55 | 0.7 | 0.75 | 0.8 | 0.024255 | 0.58783755 | 3.64328108 | 0.16134839 |
| WVDRF | 0.25 | 0.3 | 0.45 | 1 | 0.65 | 0.7 | 0.75 | 0.01151719 | 0.52850548 | 3.64328108 | 0.14506305 |
| Thermal conductivity | 0.2 | 0.25 | 0.3 | 0.35 | 1 | 0.6 | 0.65 | 0.0020475 | 0.41294207 | 3.64328108 | 0.11334346 |
| Cost | 0.15 | 0.2 | 0.25 | 0.3 | 0.4 | 1 | 0.6 | 0.00054 | 0.34134937 | 3.64328108 | 0.09369285 |
| Fire Class | 0.1 | 0.15 | 0.2 | 0.25 | 0.35 | 0.4 | 1 | 0.000105 | 0.27014596 | 3.64328108 | 0.07414908 |

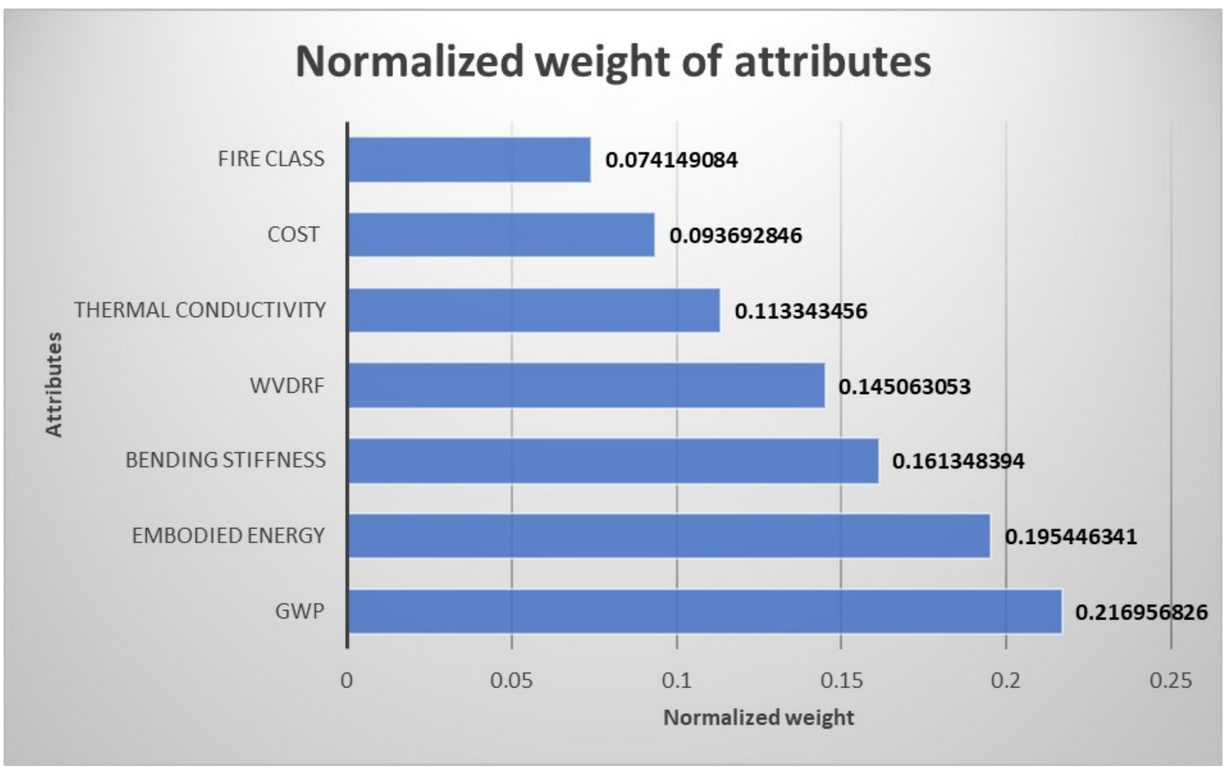


**Figure 4.8:** Normalized weight of attributes.

**Effect of normalized weights of attributes**

From the above Table 4.16 and Figure 4.8, it is evident which characteristics are considered more important by the decision maker. The reasons for the decision can be understood from the chapter where priority of attributes is discussed. The attributes which have a higher value of normalized weight will affect the final decision more than the other attributes. So, a material which has a higher rating in GWP attribute will have more influence on the final decision. In other words, Material A with higher rating in GWP will be preferred to Material B which has more rating in the attribute of cost and vice-versa.

Figure 4.9 represents the Analysis of attributes which affect the final decision in selection of best insulation material. It is seen that the final decision will be affected 40% by the attributes GWP and Embodied energy. These are the two factors which have a major impact on the emissions, and it has been emphasized that buildings sector is responsible for 40% of emissions worldwide.

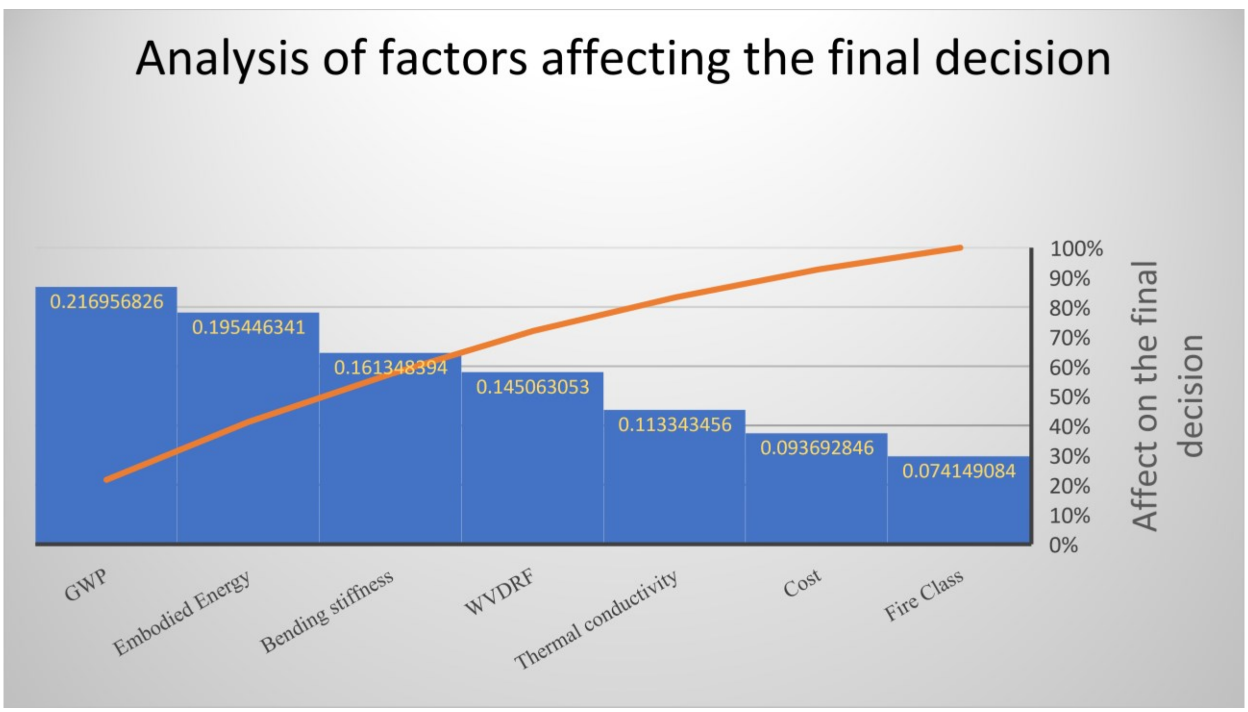


**Figure 4.9:** Analysis of factors affecting the final decision.

**Step 5: Assigning scaled weight to materials under different attributes.**

Broadly categorizing there are two kinds of attributes:

**A.** Attributes for which low value is preferred.

**B.** Attributes for which high value is preferred.

For comparison of materials against each other a best case is established which has a value of 100 on the normalized scale. Value of other materials under the attribute are then scaled with respect to the best case.

There are two ways in which best cases are decided:

**A) Lower the better:** Least value of the material in the list is preferred. To calculate the scaled weight, we use the formula:

$$Scaled\ Weight = \frac{Lowest\ value\ of\ material\ in\ the\ list}{Value\ of\ material\ under\ consideration}\ X\ 100 \qquad (4.5)$$

The attributes for which low values are preferred are as follows and scaled weight for each alternative under the attribute is shown in the last column:

**Table 4.17:** Scaled weight for GWP.

| Material | Global Warming Potential (GWP) (kg $CO_2$ eq) | Best Case | Scaled Weight |
|---|---|---|---|
| Stone Wool | 172.1536076 | 8.3074002 | 4.825574275 |
| Expanded Polystyrene | 174.1472085 | 8.3074002 | 4.770332106 |
| Polyurethane | 201.7198918 | 8.3074002 | 4.118285076 |
| Polyisocyanurate | 174.0457833 | 8.3074002 | 4.773112019 |
| Hemp Fiber | 11.9569814 | 8.3074002 | 69.47740336 |
| Kenaf | 269.6632258 | 8.3074002 | 3.080657429 |
| Flax | 94.66247623 | 8.3074002 | 8.775811209 |
| Sheep Wool | 49.46422015 | 8.3074002 | 16.79476635 |
| Coir Fiber | 8.3074002 | 8.3074002 | 100 |
| Jute Fiber | 56.02049568 | 8.3074002 | 14.82921581 |
| Fiberglass | 71.17620563 | 8.3074002 | 11.67159745 |

**Table 4.18:** Scaled weight for embodied energy.

| Material | Embodied Energy | Best Case | Scaled Weight |
|---|---|---|---|
| Stone Wool | 2463.577487 | 222.789369 | 9.043327037 |
| Expanded Polystyrene | 4390.233885 | 222.789369 | 5.074658318 |
| Polyurethane | 3087.150971 | 222.789369 | 7.216665821 |
| Polyisocyanurate | 8722.574219 | 222.789369 | 2.554169943 |
| Hemp Fiber | 1646.170463 | 222.789369 | 13.53379702 |
| Kenaf | 5050.443443 | 222.789369 | 4.411283316 |
| Flax | 4279.604493 | 222.789369 | 5.20584015 |
| Sheep Wool | 580.0188007 | 222.789369 | 38.41071509 |
| Coir Fiber | 222.789369 | 222.789369 | 100 |
| Jute Fiber | 2119.140901 | 222.789369 | 10.51319282 |
| Fiberglass | 1648.207747 | 222.789369 | 13.51706843 |

**Table 4.19:** Scaled weight for thermal conductivity.

| Material | Thermal Conductivity | Best Case | Scaled Weight |
|---|---|---|---|
| Stone Wool | 0.0365 | 0.023 | 63.01369863 |
| Expanded Polystyrene | 0.0345 | 0.023 | 66.66666667 |
| Polyurethane | 0.031 | 0.023 | 74.19354839 |
| Polyisocyanurate | 0.023 | 0.023 | 100 |
| Hemp Fiber | 0.049 | 0.023 | 46.93877551 |
| Kenaf | 0.0385 | 0.023 | 59.74025974 |
| Flax | 0.0565 | 0.023 | 40.7079646 |
| Sheep Wool | 0.046 | 0.023 | 50 |
| Coir Fiber | 0.0425 | 0.023 | 54.11764706 |
| Jute Fiber | 0.0465 | 0.023 | 49.46236559 |
| Fiberglass | 0.04 | 0.023 | 57.5 |

**Table 4.20:** Scaled weight for cost.

| Material | Cost per square foot per R-value | Best Case | Scaled Weight |
|---|---|---|---|
| Stone Wool | 0.03 | 0.02 | 66.66666667 |
| Expanded Polystyrene | 0.07 | 0.02 | 28.57142857 |
| Polyurethane | 0.02 | 0.02 | 100 |
| Polyisocyanurate | 0.1 | 0.02 | 20 |
| Hemp fiber | 0.09 | 0.02 | 22.22222222 |
| Kenaf | 0.08 | 0.02 | 25 |
| Flax | 0.6 | 0.02 | 3.333333333 |
| Sheep Wool | 0.05 | 0.02 | 40 |
| Coir Fiber | 0.14 | 0.02 | 14.28571429 |
| Jute Fiber | 0.49 | 0.02 | 4.081632653 |
| Fiberglass | 0.02 | 0.02 | 100 |

**B)** Higher the better: Highest value of the material in the list is preferred. To calculate the scaled weight, we use the formula:

$$Scaled\ Weight = \frac{Value\ of\ material\ under\ consideration}{Highest\ value\ of\ material\ in\ the\ list}\ X\ 100 \qquad (4.6)$$

The attributes for which low values are preferred are as follows and scaled weight for each alternative under the attribute is shown in the last column:

**Table 4.21:** Scaled weight for bending stiffness.

| Material | Simulated thickness (m) | E (GPa) | Bending stiffness (N-m) | Best Case | Scaled Weight |
|---|---|---|---|---|---|
| Stone Wool | 0.01835658 | 0.817 | 5.05356E-06 | 4.88459E-05 | 10.34592738 |
| Expanded Polystyrene | 0.01735074 | 2.65 | 1.3842E-05 | 4.88459E-05 | 28.33817871 |
| Polyurethane | 0.01559052 | 0.8 | 3.0316E-06 | 4.88459E-05 | 6.206458333 |
| Polyisocyanurate | 0.01156716 | 0.8 | 1.23814E-06 | 4.88459E-05 | 2.534791667 |
| Hemp Fibre | 0.02464308 | 1.45 | 2.16997E-05 | 4.88459E-05 | 44.4247526 |
| Kenaf | 0.01936242 | 1.4 | 1.01626E-05 | 4.88459E-05 | 20.80554036 |
| Flax | 0.02841498 | 1.5 | 3.44139E-05 | 4.88459E-05 | 70.45395508 |
| Sheep Wool | 0.02313432 | 1.45 | 1.7953E-05 | 4.88459E-05 | 36.75447917 |
| Coir Fiber | 0.0213741 | 1.45 | 1.4159E-05 | 4.88459E-05 | 28.98701986 |
| Jute Fiber | 0.02338578 | 1.4 | 1.79054E-05 | 4.88459E-05 | 36.65689453 |
| Fiberglass | 0.0201168 | 6 | 4.88459E-05 | 4.88459E-05 | 100 |

**Table 4.22:** Scaled weight for Water Vapor Diffusion Resistance Factor (WVDRF).

| Material | Water Vapor diffusion resistance factor | Best Case | Scaled Weight |
|---|---|---|---|
| Stone Wool | 1.15 | 102.5 | 1.12195122 |
| Expanded Polystyrene | 45 | 102.5 | 43.90243902 |
| Polyurethane | 100 | 102.5 | 97.56097561 |
| Polyisocyanurate | 102.5 | 102.5 | 100 |
| Hemp Fibre | 1.5 | 102.5 | 1.463414634 |
| Kenaf | 1.75 | 102.5 | 1.707317073 |
| Flax | 1.5 | 102.5 | 1.463414634 |
| Sheep Wool | 2 | 102.5 | 1.951219512 |
| Coir Fiber | 17.5 | 102.5 | 17.07317073 |
| Jute Fiber | 1.5 | 102.5 | 1.463414634 |
| Fiberglass | 1.05 | 102.5 | 1.024390244 |

- Fire Class

For this attribute we have established a rating scale for different grades. This is shown in Table 4.23 followed by the scaled weight table (4.24) for each alternative.

**Table 4.23:** Rating scale for fire class.

| Grade | Rating |
|---|---|
| A1 | 100 |
| A2 | 90 |
| B | 75 |
| C | 60 |
| D | 45 |
| E | 30 |
| F | 15 |

**Table 4.24:** Scaled weight for fire class.

| Material | Fire class | Weight | Best case | Scaled weight |
|---|---|---|---|---|
| Stone Wool | A1-A2-B | 90 | 90 | 100 |
| Expanded Polystyrene | E | 30 | 90 | 33.33333333 |
| Polyurethane | E | 30 | 90 | 33.33333333 |
| Polyisocyanurate | B | 75 | 90 | 83.33333333 |
| Hemp Fiber | E | 30 | 90 | 33.33333333 |
| Kenaf | D-E | 37.5 | 90 | 41.66666667 |
| Flax | E | 30 | 90 | 33.33333333 |
| Sheep Wool | E | 30 | 90 | 33.33333333 |
| Coir Fiber | D-E | 37.5 | 90 | 41.66666667 |
| Jute Fiber | E | 30 | 90 | 33.33333333 |
| Fiberglass | A1-A2 | 90 | 90 | 100 |

Intermediate values of weights are taken for materials which fall under multiple Fire class rating

**Step 6: Calculation of normalized weight of alternatives under different attributes**

To check the performance of alternatives against each other we use the scaled weights calculated earlier. The figures shown below the tables in this section represent the comparative performance of each alternative under various attributes against each other.

Method to find the normalized weight (which corresponds to the last column), is mentioned in the steps below.

- First, we find the product of all the values in the row corresponding to the attribute.
- Next, we calculate Geometric Mean (GM) of each row product given by:

  GM = (Row Product)$^{(1/n)}$, where n = no of attributes (7 for our analysis)

- Next, we sum all the geometric means to find normalized weight. The last cell of the GM column gives the sum of GMs.
- To calculate the normalized weight, we divide the GM of each attribute by the sum of GMs.
- This last column of Normalized weight will later be used in the decision matrix. The graph below the tables in the next section shows the performance of each alternative under the various attributes.

## Attribute 1: Global Warming Potential (GWP)

**Table 4.25:** Calculation of normalized weight for GWP.

| GWP | Stone wool | XPS | Polyurethane | Polyisocyanurate | Hemp | Kenaf | Flax | Sheep wool | Coir | Jute | Fibre Glass | Row Product | Geometric mean | Sum of GM | Normalized weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 1.00 | 1.01 | 1.17 | 1.01 | 0.07 | 1.57 | 0.55 | 0.29 | 0.05 | 0.33 | 0.41 | 0.000133729 | 0.44446625 | 22.783764 | 0.01950803 |
| Expanded Polystyrene | 0.99 | 1.00 | 1.16 | 1.00 | 0.07 | 1.55 | 0.54 | 0.28 | 0.05 | 0.32 | 0.41 | 0.000117821 | 0.43937809 | 22.783764 | 0.0192847 |
| Polyurethane | 0.85 | 0.86 | 1.00 | 0.86 | 0.06 | 1.34 | 0.47 | 0.25 | 100.00 | 0.28 | 0.35 | 0.05680044 | 0.77047623 | 22.783764 | 0.0338169 |
| Polyisocyanurate | 0.99 | 1.00 | 1.16 | 1.00 | 0.07 | 1.55 | 0.54 | 0.28 | 0.05 | 0.32 | 0.41 | 0.000118578 | 0.43963414 | 22.783764 | 0.01929594 |
| Hemp Fibre | 14.40 | 14.56 | 16.87 | 14.56 | 1.00 | 22.55 | 7.92 | 4.14 | 0.69 | 4.69 | 5.95 | 736999179.5 | 6.39931317 | 22.783764 | 0.28087164 |
| Kenaf | 0.64 | 0.65 | 0.75 | 0.65 | 0.04 | 1.00 | 0.35 | 0.18 | 0.03 | 0.21 | 0.26 | 9.59986E-07 | 0.28374825 | 22.783764 | 0.01245397 |
| Flax | 1.82 | 1.84 | 2.13 | 1.84 | 0.13 | 2.85 | 1.00 | 0.52 | 0.09 | 0.59 | 0.75 | 0.09623823 | 0.80830833 | 22.783764 | 0.03547738 |
| Sheep Wool | 3.48 | 3.52 | 4.08 | 3.52 | 0.24 | 5.45 | 1.91 | 1.00 | 0.17 | 1.13 | 1.44 | 121.3671813 | 1.54690539 | 22.783764 | 0.06789508 |
| Coir Fiber | 20.72 | 20.96 | 24.28 | 20.95 | 1.44 | 32.46 | 11.39 | 5.95 | 1.00 | 6.74 | 8.57 | 40475072669 | 9.21063951 | 22.783764 | 0.4042633 |
| Jute Fiber | 3.07 | 3.11 | 3.60 | 3.11 | 0.21 | 4.81 | 1.69 | 0.88 | 0.15 | 1.00 | 1.27 | 30.86652062 | 1.36586561 | 22.783764 | 0.05994908 |
| Fibre glass | 2.42 | 2.45 | 2.83 | 2.45 | 0.17 | 3.79 | 1.33 | 0.69 | 0.12 | 0.79 | 1.00 | 2.216261191 | 1.07502877 | 22.783764 | 0.04718398 |
| | | | | | | | | | | | | Sum | 22.7837637 | | |

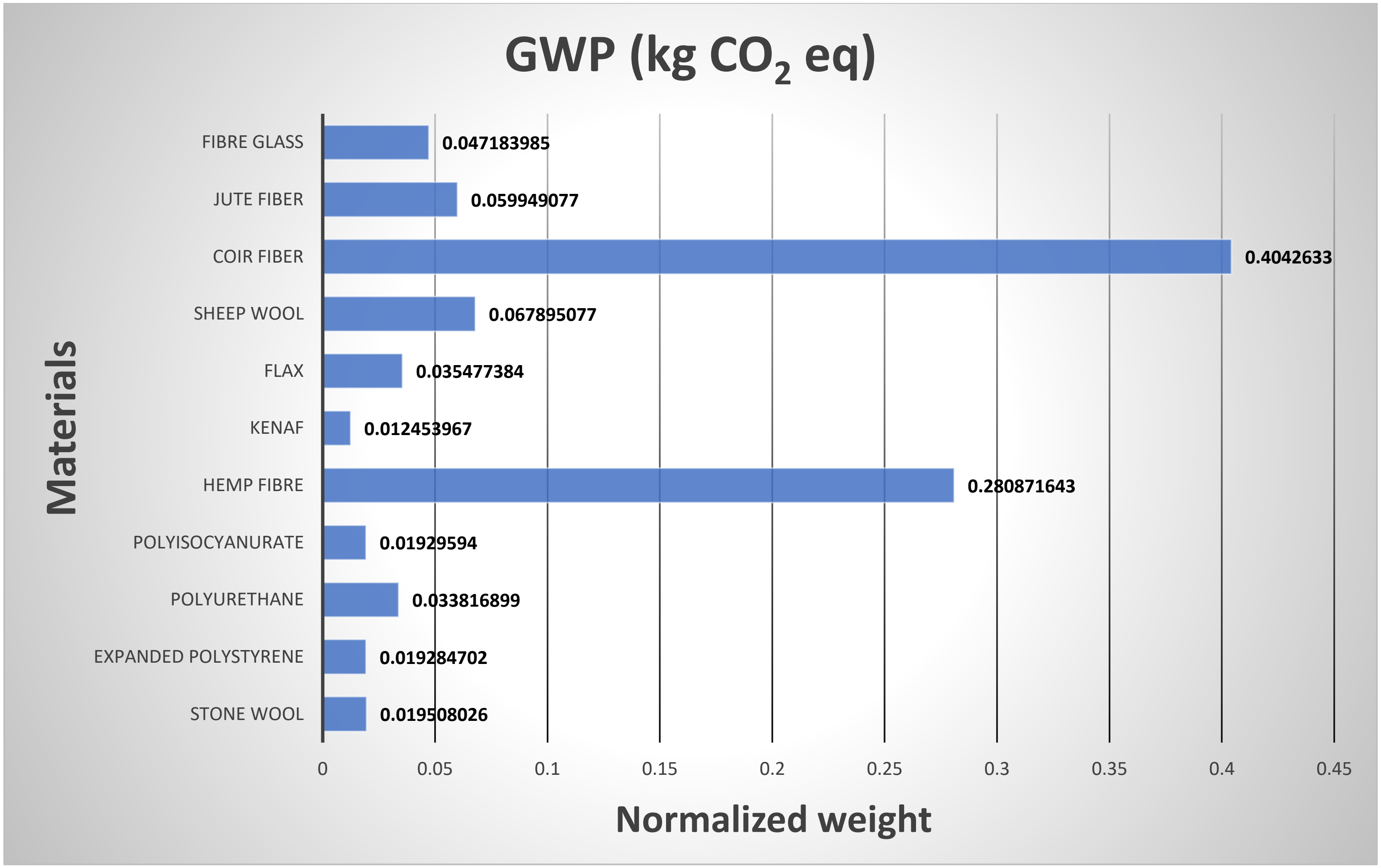


**Figure 4.10:** Graph for normalized weight of materials (GWP).

**Attribute 2: Embodied Energy**

**Table 4.26:** Calculation of normalized weight for embodied energy.

| Embodied energy | Stone wool | XPS | Polyurethane | Polyisocyanurate | Hemp | Kenaf | Flax | Sheep wool | Coir | Jute | Fibre Glass | Row Product | Geometric mean | Sum of GM | Normalized weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 1.00 | 1.78 | 1.25 | 3.54 | 0.67 | 2.05 | 1.74 | 0.24 | 0.09 | 0.86 | 0.67 | 0.230539 | 0.88 | 20.27 | 0.04317317 |
| Expanded Polystyrene | 0.56 | 1.00 | 0.70 | 1.99 | 0.37 | 1.15 | 0.97 | 0.13 | 0.05 | 0.48 | 0.38 | 0.000401 | 0.49 | 20.27 | 0.0242266 |
| Polyurethane | 0.80 | 1.42 | 1.00 | 2.83 | 0.53 | 1.64 | 1.39 | 0.19 | 0.07 | 0.69 | 0.53 | 0.019268 | 0.70 | 20.27 | 0.03445262 |
| Polyisocyanurate | 0.28 | 0.50 | 0.35 | 1.00 | 0.19 | 0.58 | 0.49 | 0.07 | 0.03 | 0.24 | 0.19 | 0.000000 | 0.25 | 20.27 | 0.0121937 |
| Hemp Fibre | 1.50 | 2.67 | 1.88 | 5.30 | 1.00 | 3.07 | 2.60 | 0.35 | 0.14 | 1.29 | 1.00 | 19.442399 | 1.31 | 20.27 | 0.06461083 |
| Kenaf | 0.49 | 0.87 | 0.61 | 1.73 | 0.33 | 1.00 | 0.85 | 0.11 | 0.04 | 0.42 | 0.33 | 0.000086 | 0.43 | 20.27 | 0.02105962 |
| Flax | 0.58 | 1.03 | 0.72 | 2.04 | 0.38 | 1.18 | 1.00 | 0.14 | 0.05 | 0.50 | 0.39 | 0.000530 | 0.50 | 20.27 | 0.02485287 |
| Sheep Wool | 4.25 | 7.57 | 5.32 | 15.04 | 2.84 | 8.71 | 7.38 | 1.00 | 0.38 | 3.65 | 2.84 | 1871155.655274 | 3.72 | 20.27 | 0.18337413 |
| Coir Fiber | 11.06 | 19.71 | 13.86 | 39.15 | 7.39 | 22.67 | 19.21 | 2.60 | 1.00 | 9.51 | 7.40 | 69684084556.112800 | 9.68 | 20.27 | 0.47740358 |
| Jute Fiber | 1.16 | 2.07 | 1.46 | 4.12 | 0.78 | 2.38 | 2.02 | 0.27 | 0.11 | 1.00 | 0.78 | 1.208411 | 1.02 | 20.27 | 0.05019036 |
| Fibre glass | 1.49 | 2.66 | 1.87 | 5.29 | 1.00 | 3.06 | 2.60 | 0.35 | 0.14 | 1.29 | 1.00 | 19.179675 | 1.31 | 20.27 | 0.06453097 |
| | | | | | | | | | | | | Sum | 20.27 | | |

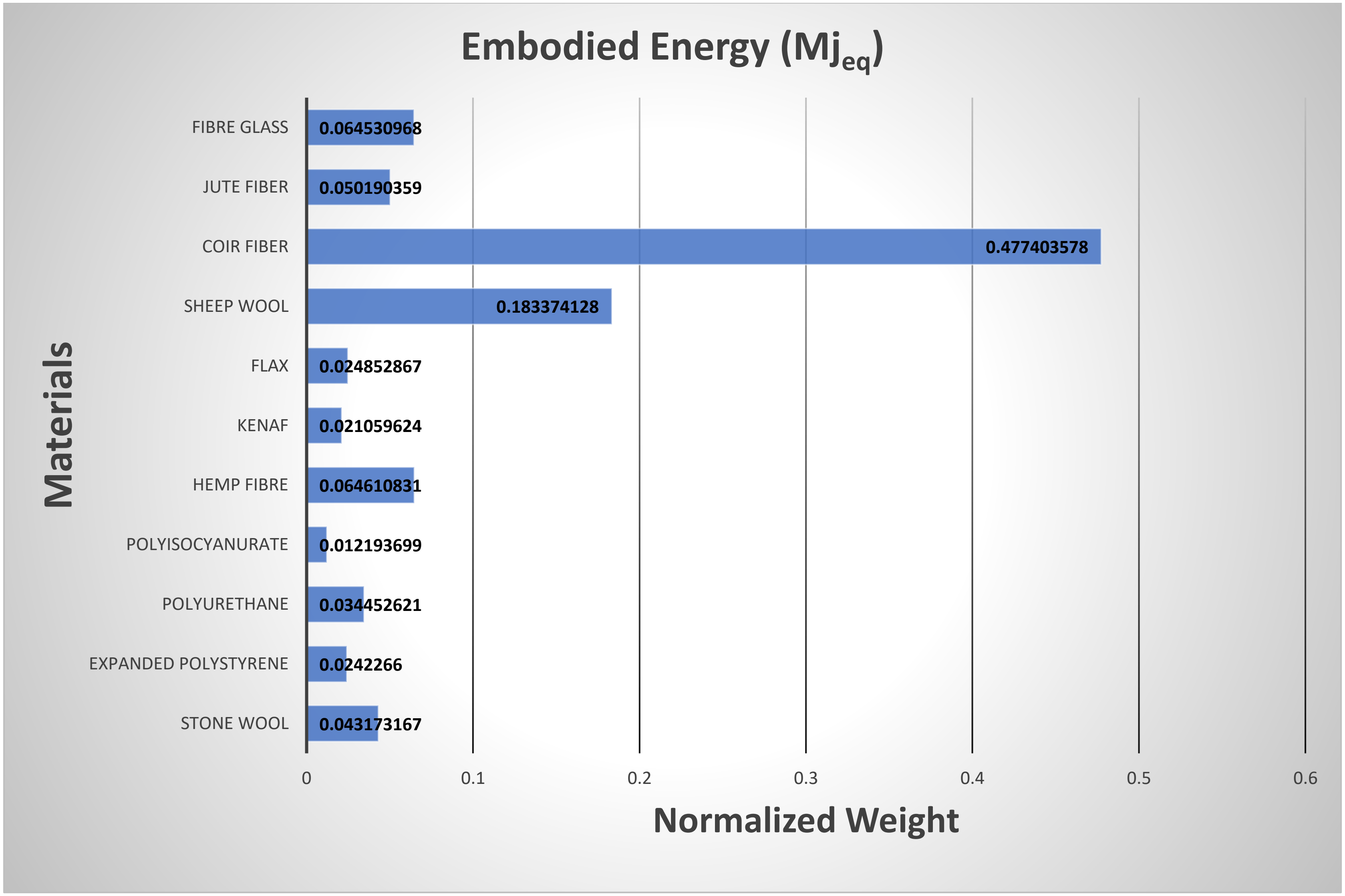


**Figure 4.11:** Graph for normalized weight of materials (Embodied energy).

**Attribute 3: Bending Stiffness**

**Table 4.27:** Calculation of normalized weight for bending stiffness.

| Bending stiffness | Stone wool | XPS | Polyurethane | Polyisocyanurate | Hemp | Kenaf | Flax | Sheep wool | Coir | Jute | Fibre Glass | Row Product | Geometric mean | Sum of GM | Normalized weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 1.00 | 0.37 | 1.67 | 4.08 | 0.23 | 0.50 | 0.15 | 0.28 | 0.36 | 0.28 | 0.10 | 0.000123925 | 0.44140016 | 16.447369 | 0.02683713 |
| Expanded Polystyrene | 2.74 | 1.00 | 4.57 | 11.18 | 0.64 | 1.36 | 0.40 | 0.77 | 0.98 | 0.77 | 0.28 | 8.068353183 | 1.20902419 | 16.447369 | 0.07350867 |
| Polyurethane | 0.60 | 0.22 | 1.00 | 2.45 | 0.14 | 0.30 | 0.09 | 0.17 | 0.21 | 0.17 | 0.06 | 4.4872E-07 | 0.26479324 | 16.447369 | 0.01609943 |
| Polyisocyanurate | 0.25 | 0.09 | 0.41 | 1.00 | 0.06 | 0.12 | 0.04 | 0.07 | 0.09 | 0.07 | 0.03 | 2.36624E-11 | 0.10814472 | 16.447369 | 0.0065752 |
| Hemp Fibre | 4.29 | 1.57 | 7.16 | 17.53 | 1.00 | 2.14 | 0.63 | 1.21 | 1.53 | 1.21 | 0.44 | 1133.884492 | 1.89534413 | 16.447369 | 0.11523692 |
| Kenaf | 2.01 | 0.73 | 3.35 | 8.21 | 0.47 | 1.00 | 0.30 | 0.57 | 0.72 | 0.57 | 0.21 | 0.269564449 | 0.88765061 | 16.447369 | 0.05396915 |
| Flax | 6.81 | 2.49 | 11.35 | 27.79 | 1.59 | 3.39 | 1.00 | 1.92 | 2.43 | 1.92 | 0.70 | 180989.2489 | 3.00585782 | 16.447369 | 0.18275614 |
| Sheep Wool | 3.55 | 1.30 | 5.92 | 14.50 | 0.83 | 1.77 | 0.52 | 1.00 | 1.27 | 1.00 | 0.37 | 140.9634824 | 1.56809846 | 16.447369 | 0.09534038 |
| Coir Fiber | 2.80 | 1.02 | 4.67 | 11.44 | 0.65 | 1.39 | 0.41 | 0.79 | 1.00 | 0.79 | 0.29 | 10.34982166 | 1.23670645 | 16.447369 | 0.07519175 |
| Jute Fiber | 3.54 | 1.29 | 5.91 | 14.46 | 0.83 | 1.76 | 0.52 | 1.00 | 1.26 | 1.00 | 0.37 | 136.9008006 | 1.5639351 | 16.447369 | 0.09508725 |
| Fibre glass | 9.67 | 3.53 | 16.11 | 39.45 | 2.25 | 4.81 | 1.42 | 2.72 | 3.45 | 2.73 | 1.00 | 8524984.892 | 4.26641459 | 16.447369 | 0.25939799 |
| | | | | | | | | | | | | sum | 16.4473695 | | |

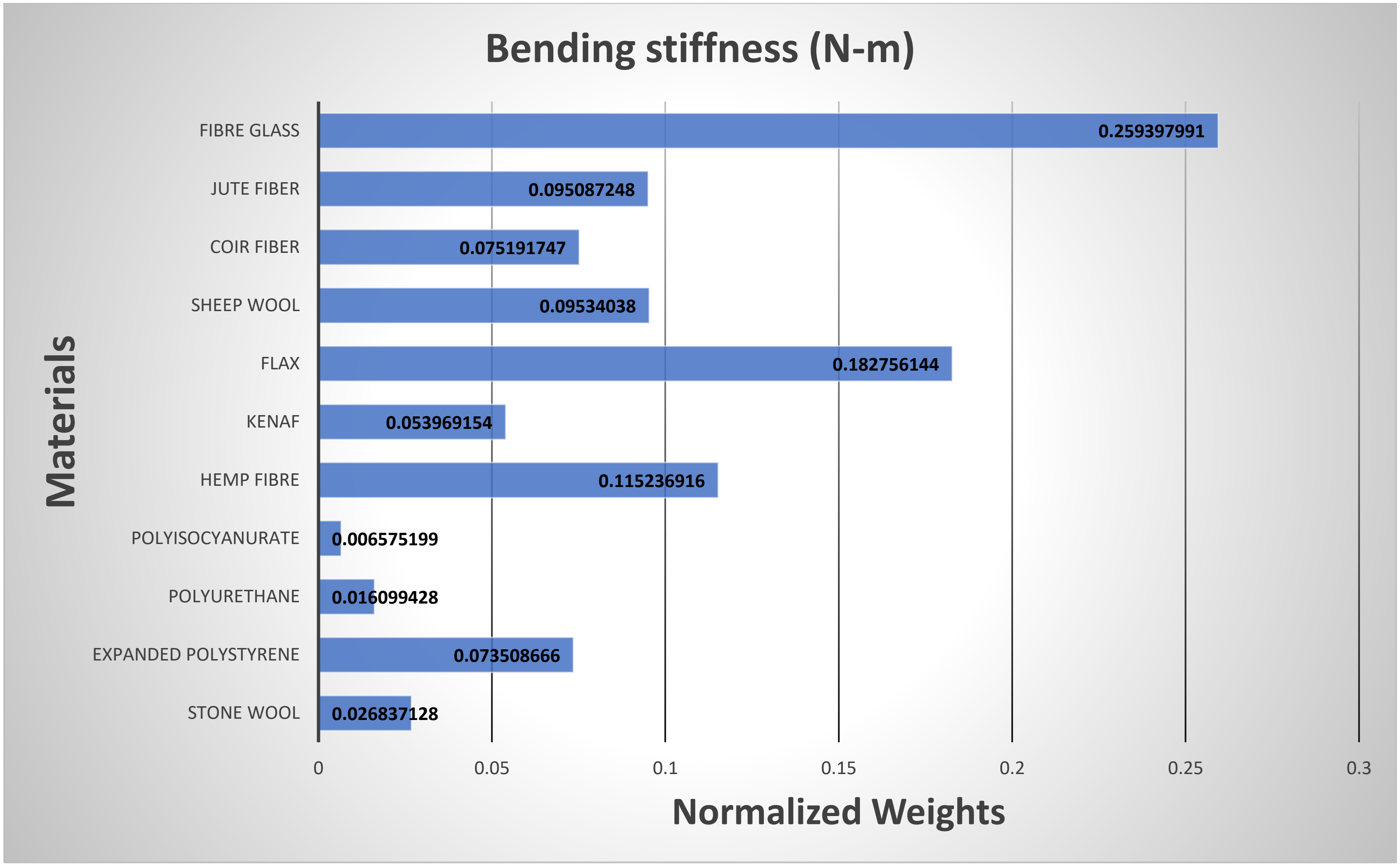


**Figure 4.12:** Graph for normalized weight of materials (Bending stiffness).

**Attribute 4: Water Vapor Diffusion Resistance Coefficient (WVDRF)**

**Table 4.28:** Calculation of normalized weight for WVDRF.

| WVDRF | Stone wool | XPS | Polyurethane | Polyisocyanurate | Hemp | Kenaf | Flax | Sheep wool | Coir | Jute | Fibre Glass | Row Product | Geometric mean | Sum of GM | Normalized weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 1.00 | 0.03 | 0.01 | 0.01 | 0.77 | 0.66 | 0.77 | 0.58 | 0.07 | 0.77 | 1.10 | 4.04085E-08 | 0.21274589 | 50.957264 | 0.00417499 |
| Expanded Polystyrene | 39.13 | 1.00 | 0.45 | 0.44 | 30.00 | 25.71 | 30.00 | 22.50 | 2.57 | 30.00 | 42.86 | 13308657934 | 8.32483898 | 50.957264 | 0.16336903 |
| Polyurethane | 86.96 | 2.22 | 1.00 | 0.98 | 66.67 | 57.14 | 66.67 | 50.00 | 5.71 | 66.67 | 95.24 | 8.68554E+13 | 18.4996422 | 50.957264 | 0.36304229 |
| Polyisocyanurate | 89.13 | 2.28 | 1.03 | 1.00 | 68.33 | 58.57 | 68.33 | 51.25 | 5.86 | 68.33 | 97.62 | 1.13962E+14 | 18.9621332 | 50.957264 | 0.37211835 |
| Hemp Fibre | 1.30 | 0.03 | 0.02 | 0.01 | 1.00 | 0.86 | 1.00 | 0.75 | 0.09 | 1.00 | 1.43 | 7.51278E-07 | 0.27749463 | 50.957264 | 0.00544563 |
| Kenaf | 1.52 | 0.04 | 0.02 | 0.02 | 1.17 | 1.00 | 1.17 | 0.88 | 0.10 | 1.17 | 1.67 | 4.09463E-06 | 0.32374374 | 50.957264 | 0.00635324 |
| Flax | 1.30 | 0.03 | 0.02 | 0.01 | 1.00 | 0.86 | 1.00 | 0.75 | 0.09 | 1.00 | 1.43 | 7.51278E-07 | 0.27749463 | 50.957264 | 0.00544563 |
| Sheep Wool | 1.74 | 0.04 | 0.02 | 0.02 | 1.33 | 1.14 | 1.33 | 1.00 | 0.11 | 1.33 | 1.90 | 1.7788E-05 | 0.36999284 | 50.957264 | 0.00726085 |
| Coir Fiber | 15.22 | 0.39 | 0.18 | 0.17 | 11.67 | 10.00 | 11.67 | 8.75 | 1.00 | 11.67 | 16.67 | 409463.4551 | 3.23743738 | 50.957264 | 0.0635324 |
| Jute Fiber | 1.30 | 0.03 | 0.02 | 0.01 | 1.00 | 0.86 | 1.00 | 0.75 | 0.09 | 1.00 | 1.43 | 7.51278E-07 | 0.27749463 | 50.957264 | 0.00544563 |
| Fibre glass | 0.91 | 0.02 | 0.01 | 0.01 | 0.70 | 0.60 | 0.70 | 0.53 | 0.06 | 0.70 | 1.00 | 1.48552E-08 | 0.19424624 | 50.957264 | 0.00381194 |
| | | | | | | | | | | | | sum | 50.9572644 | | |

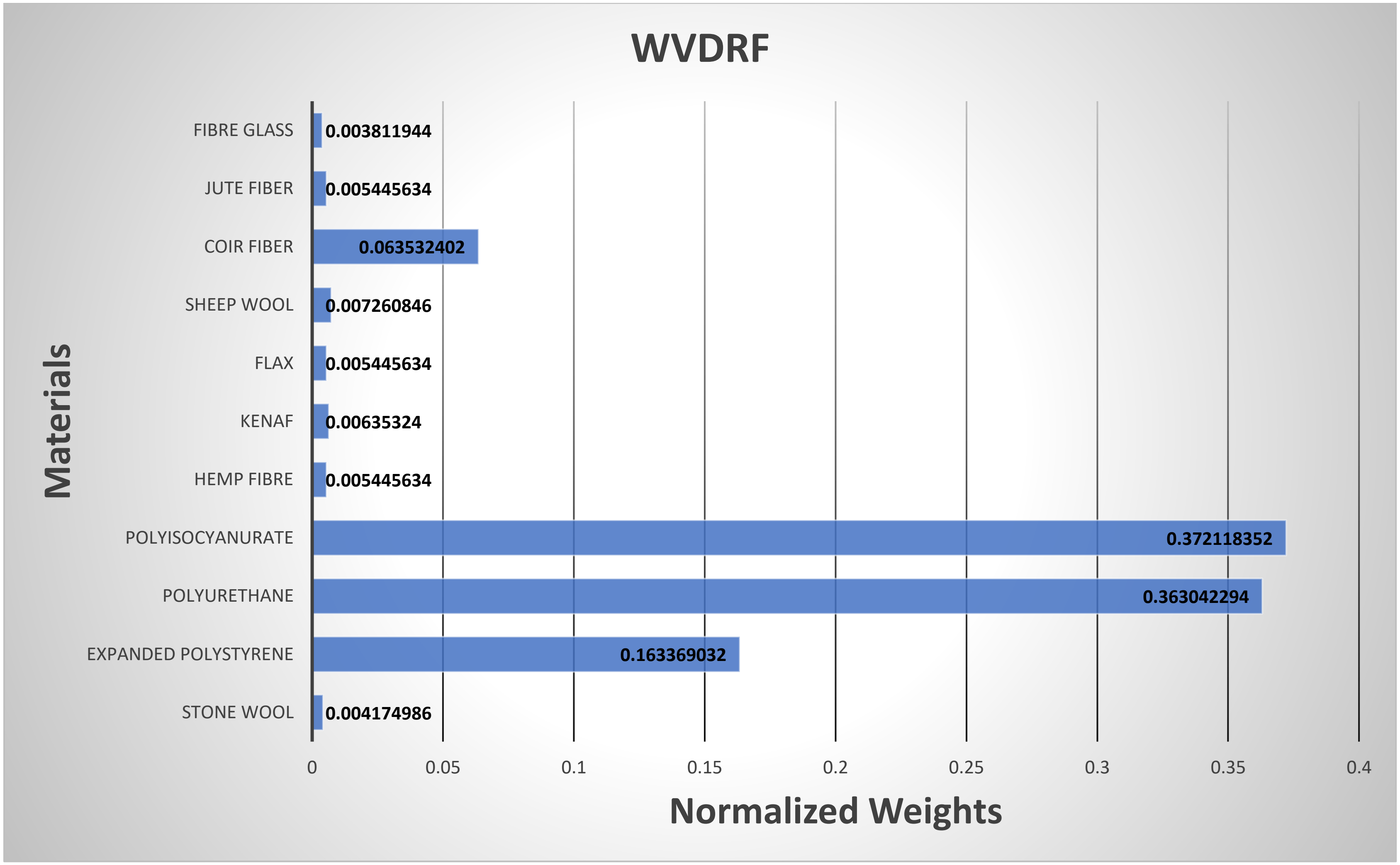


**Figure 4.13:** Graph for normalized weight of materials (WVDRF).

**Attribute 5: Thermal Conductivity**

**Table 4.29:** Calculation of normalized weight for thermal conductivity.

| Thermal Conductivity | Stone wool | XPS | Polyurethane | Polyisocyan urate | Hemp | Kenaf | Flax | Sheep wool | Coir | Jute | Fibre Glass | Row Product | Geometric mean | Sum of GM | Normalized weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 1.00 | 0.95 | 0.85 | 0.63 | 1.34 | 1.05 | 1.55 | 1.26 | 1.16 | 1.27 | 1.10 | 2.271668436 | 1.07744471 | 11.325089 | 0.09513786 |
| Expanded Polystyrene | 1.06 | 1.00 | 0.90 | 0.67 | 1.42 | 1.12 | 1.64 | 1.33 | 1.23 | 1.35 | 1.16 | 4.222371163 | 1.13990528 | 11.325089 | 0.1006531 |
| Polyurethane | 1.18 | 1.11 | 1.00 | 0.74 | 1.58 | 1.24 | 1.82 | 1.48 | 1.37 | 1.50 | 1.29 | 13.69581309 | 1.26860426 | 11.325089 | 0.11201716 |
| Polyisocyanurate | 1.59 | 1.50 | 1.35 | 1.00 | 2.13 | 1.67 | 2.46 | 2.00 | 1.85 | 2.02 | 1.74 | 365.2247971 | 1.70985792 | 11.325089 | 0.15097965 |
| Hemp Fibre | 0.74 | 0.70 | 0.63 | 0.47 | 1.00 | 0.79 | 1.15 | 0.94 | 0.87 | 0.95 | 0.82 | 0.08900401 | 0.80258637 | 11.325089 | 0.070868 |
| Kenaf | 0.95 | 0.90 | 0.81 | 0.60 | 1.27 | 1.00 | 1.47 | 1.19 | 1.10 | 1.21 | 1.04 | 1.263276531 | 1.02147356 | 11.325089 | 0.09019563 |
| Flax | 0.65 | 0.61 | 0.55 | 0.41 | 0.87 | 0.68 | 1.00 | 0.81 | 0.75 | 0.82 | 0.71 | 0.018579479 | 0.69604836 | 11.325089 | 0.06146074 |
| Sheep Wool | 0.79 | 0.75 | 0.67 | 0.50 | 1.07 | 0.84 | 1.23 | 1.00 | 0.92 | 1.01 | 0.87 | 0.17833242 | 0.85492896 | 11.325089 | 0.07548982 |
| Coir Fiber | 0.86 | 0.81 | 0.73 | 0.54 | 1.15 | 0.91 | 1.33 | 1.08 | 1.00 | 1.09 | 0.94 | 0.425880958 | 0.92533487 | 11.325089 | 0.08170663 |
| Jute Fiber | 0.78 | 0.74 | 0.67 | 0.49 | 1.05 | 0.83 | 1.22 | 0.99 | 0.91 | 1.00 | 0.86 | 0.158337568 | 0.84573617 | 11.325089 | 0.07467811 |
| Fibre glass | 0.91 | 0.86 | 0.78 | 0.58 | 1.23 | 0.96 | 1.41 | 1.15 | 1.06 | 1.16 | 1.00 | 0.829672219 | 0.9831683 | 11.325089 | 0.0868133 |
| | | | | | | | | | | | | sum | 11.3250888 | | |

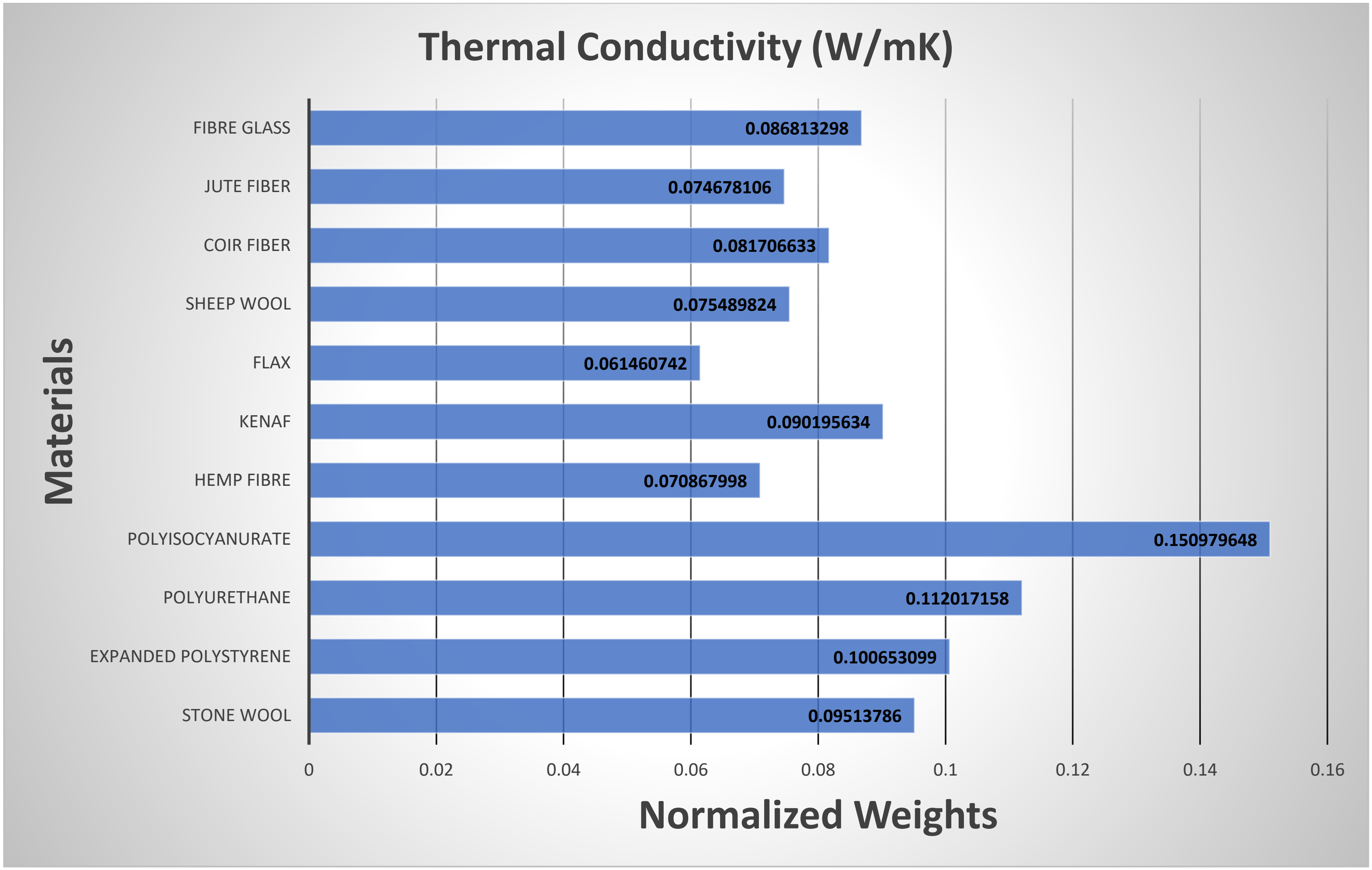


**Figure 4.14:** Graph for normalized weight of materials (Thermal conductivity).

## Attribute 6: Cost

**Table 4.30:** Calculation of normalized weight for cost.

| Cost | Stone wool | XPS | Polyurethane | Polyisocyanurate | Hemp | Kenaf | Flax | Sheep wool | Coir | Jute | Fibre Glass | Row Product | Geometric mean | Sum of GM | Normalized weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 1.00 | 2.33 | 0.67 | 3.33 | 3.00 | 2.67 | 20.00 | 1.67 | 4.67 | 16.33 | 0.67 | 70262.45999 | 2.75810766 | 17.548225 | 0.15717302 |
| Expanded Polystyrene | 0.43 | 1.00 | 0.29 | 1.43 | 1.29 | 1.14 | 8.57 | 0.71 | 2.00 | 7.00 | 0.29 | 6.294753279 | 1.18204614 | 17.548225 | 0.06735987 |
| Polyurethane | 1.50 | 3.50 | 1.00 | 5.00 | 4.50 | 4.00 | 30.00 | 2.50 | 7.00 | 24.50 | 1.00 | 6077531.25 | 4.13716148 | 17.548225 | 0.23575954 |
| Polyisocyanurate | 0.30 | 0.70 | 0.20 | 1.00 | 0.90 | 0.80 | 6.00 | 0.50 | 1.40 | 4.90 | 0.20 | 0.12446784 | 0.8274323 | 17.548225 | 0.04715191 |
| Hemp Fibre | 0.33 | 0.78 | 0.22 | 1.11 | 1.00 | 0.89 | 6.67 | 0.56 | 1.56 | 5.44 | 0.22 | 0.396633643 | 0.91936922 | 17.548225 | 0.05239101 |
| Kenaf | 0.38 | 0.88 | 0.25 | 1.25 | 1.13 | 1.00 | 7.50 | 0.63 | 1.75 | 6.13 | 0.25 | 1.448996365 | 1.03429037 | 17.548225 | 0.05893988 |
| Flax | 0.05 | 0.12 | 0.03 | 0.17 | 0.15 | 0.13 | 1.00 | 0.08 | 0.23 | 0.82 | 0.03 | 3.43078E-10 | 0.13790538 | 17.548225 | 0.00785865 |
| Sheep Wool | 0.60 | 1.40 | 0.40 | 2.00 | 1.80 | 1.60 | 12.00 | 1.00 | 2.80 | 9.80 | 0.40 | 254.9101363 | 1.65486459 | 17.548225 | 0.09430381 |
| Coir Fiber | 0.21 | 0.50 | 0.14 | 0.71 | 0.64 | 0.57 | 4.29 | 0.36 | 1.00 | 3.50 | 0.14 | 0.00307361 | 0.59102307 | 17.548225 | 0.03367993 |
| Jute Fiber | 0.06 | 0.14 | 0.04 | 0.20 | 0.18 | 0.16 | 1.22 | 0.10 | 0.29 | 1.00 | 0.04 | 3.18347E-09 | 0.16886373 | 17.548225 | 0.00962284 |
| Fibre glass | 1.50 | 3.50 | 1.00 | 5.00 | 4.50 | 4.00 | 30.00 | 2.50 | 7.00 | 24.50 | 1.00 | 6077531.25 | 4.13716148 | 17.548225 | 0.23575954 |
| | | | | | | | | | | | | Sum | 17.5482254 | | |

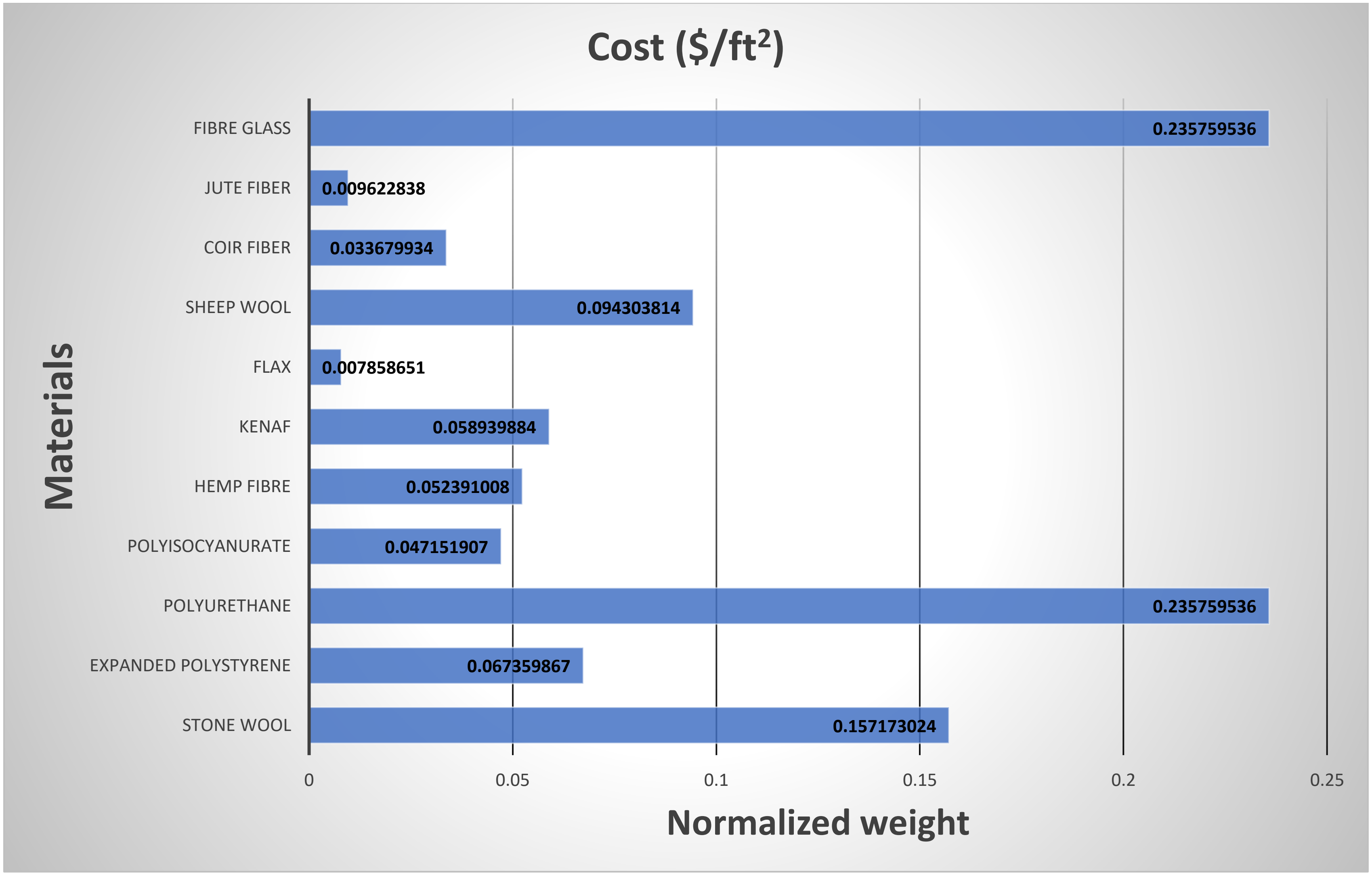


**Figure 4.15:** Graph for normalized weight of materials (cost).

**<u>Attribute 7: Fire Class</u>**

**Table 4.31:** Calculation of normalized weight fire class.

| Fire class | Stone wool | XPS | Polyurethane | Polyisocyanurate | Hemp | Kenaf | Flax | Sheep wool | Coir | Jute | Fibre Glass | Row Product | Geometric mean | Sum of GM | Normalized weight |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stone Wool | 1.00 | 3.00 | 3.00 | 1.20 | 3.00 | 2.40 | 3.00 | 3.00 | 2.40 | 3.00 | 1.00 | 5038.848 | 2.17057886 | 12.299947 | 0.17647059 |
| Expanded Polystyrene | 0.33 | 1.00 | 1.00 | 0.40 | 1.00 | 0.80 | 1.00 | 1.00 | 0.80 | 1.00 | 0.33 | 0.028444444 | 0.72352629 | 12.299947 | 0.05882353 |
| Polyurethane | 0.33 | 1.00 | 1.00 | 0.40 | 1.00 | 0.80 | 1.00 | 1.00 | 0.80 | 1.00 | 0.33 | 0.028444444 | 0.72352629 | 12.299947 | 0.05882353 |
| Polyisocyanurate | 0.83 | 2.50 | 2.50 | 1.00 | 2.50 | 2.00 | 2.50 | 2.50 | 2.00 | 2.50 | 0.83 | 678.1684028 | 1.80881572 | 12.299947 | 0.14705882 |
| Hemp Fibre | 0.33 | 1.00 | 1.00 | 0.40 | 1.00 | 0.80 | 1.00 | 1.00 | 0.80 | 1.00 | 0.33 | 0.028444444 | 0.72352629 | 12.299947 | 0.05882353 |
| Kenaf | 0.42 | 1.25 | 1.25 | 0.50 | 1.25 | 1.00 | 1.25 | 1.25 | 1.00 | 1.25 | 0.42 | 0.331136915 | 0.90440786 | 12.299947 | 0.07352941 |
| Flax | 0.33 | 1.00 | 1.00 | 0.40 | 1.00 | 0.80 | 1.00 | 1.00 | 0.80 | 1.00 | 0.33 | 0.028444444 | 0.72352629 | 12.299947 | 0.05882353 |
| Sheep Wool | 0.33 | 1.00 | 1.00 | 0.40 | 1.00 | 0.80 | 1.00 | 1.00 | 0.80 | 1.00 | 0.33 | 0.028444444 | 0.72352629 | 12.299947 | 0.05882353 |
| Coir Fiber | 0.42 | 1.25 | 1.25 | 0.50 | 1.25 | 1.00 | 1.25 | 1.25 | 1.00 | 1.25 | 0.42 | 0.331136915 | 0.90440786 | 12.299947 | 0.07352941 |
| Jute Fiber | 0.33 | 1.00 | 1.00 | 0.40 | 1.00 | 0.80 | 1.00 | 1.00 | 0.80 | 1.00 | 0.33 | 0.028444444 | 0.72352629 | 12.299947 | 0.05882353 |
| Fibre glass | 1.00 | 3.00 | 3.00 | 1.20 | 3.00 | 2.40 | 3.00 | 3.00 | 2.40 | 3.00 | 1.00 | 5038.848 | 2.17057886 | 12.299947 | 0.17647059 |
| | | | | | | | | | | | | sum | 12.2999469 | | |

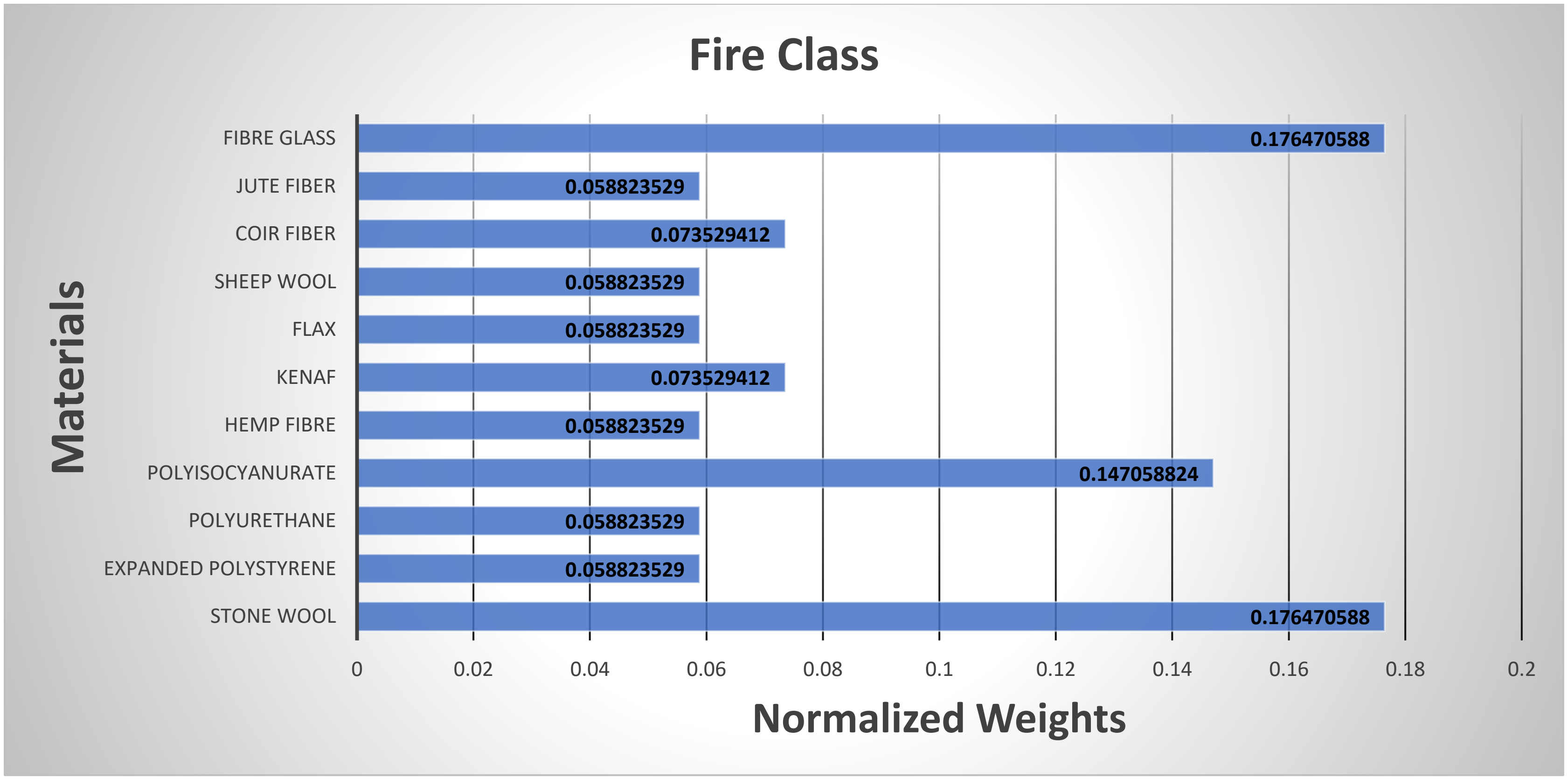


**Figure 4.16:** Graph for normalized weight of materials (fire class).

**Step 7: Creating the decision matrix**

We will create a new matrix of the following order:
1st row : Name of all 7 attributes.

2nd row: Normalized weight of each attribute obtained from Table 4.16. The value of normalized weights for all attributes are entered right below them, as shown in the table below:

**Table 4.32:** Step 1 to form decision matrix.

| Attributes | GWP | Embodied Energy | Bending stiffness | WVDRF | Thermal conductivity | Cost | Fire Class |
|---|---|---|---|---|---|---|---|
| Normalized weight | 0.216956826 | 0.195446341 | 0.161348394 | 0.14506305 | 0.11334346 | 0.09369285 | 0.07414908 |

All the rows after that will have normalized values taken from tables 4.25 to 4.31 of all alternatives under various attributes. For example, consider Stone Wool (our 1st alternate), it has normalized weights under each attribute. We collect the normalized weights of Stone Wool from various attributes from Tables 4.25, 4.26, 4.27, 4.28, 4.29, 4.30 & 4.31 and assemble them in the 3rd row of Table 4.33. So, the first three rows of our decision matrix would look like the one shown below:

**Table 4.33:** Step 2 to form decision matrix.

| Attributes | GWP | Embodied Energy | Bending stiffness | WVDRF | Thermal conductivity | Cost | Fire Class |
|---|---|---|---|---|---|---|---|
| Normalized weight | 0.216956826 | 0.195446341 | 0.161348394 | 0.14506305 | 0.11334346 | 0.09369285 | 0.07414908 |
| Stone Wool | 0.019508026 | 0.043173167 | 0.026837128 | 0.00417499 | 0.09513786 | 0.15717302 | 0.17647059 |

We do this for all following alternatives and form a part of the decision matrix as shown below.

**Table 4.34:** Step 3 to form decision matrix.

| Attributes | GWP | Embodied Energy | Bending stiffness | WVDRF | Thermal conductivity | Cost | Fire Class |
|---|---|---|---|---|---|---|---|
| Normalized weight | 0.216956826 | 0.195446341 | 0.161348394 | 0.14506305 | 0.11334346 | 0.09369285 | 0.07414908 |
| Stone Wool | 0.019508026 | 0.043173167 | 0.026837128 | 0.00417499 | 0.09513786 | 0.15717302 | 0.17647059 |
| Expanded Polystyrene | 0.019284702 | 0.0242266 | 0.073508666 | 0.16336903 | 0.1006531 | 0.06735987 | 0.05882353 |
| Polyurethane | 0.033816899 | 0.034452621 | 0.016099428 | 0.36304229 | 0.11201716 | 0.23575954 | 0.05882353 |
| Polyisocyanurate | 0.01929594 | 0.012193699 | 0.006575199 | 0.37211835 | 0.15097965 | 0.04715191 | 0.14705882 |
| Hemp Fibre | 0.280871643 | 0.064610831 | 0.115236916 | 0.00544563 | 0.070868 | 0.05239101 | 0.05882353 |
| Kenaf | 0.012453967 | 0.021059624 | 0.053969154 | 0.00635324 | 0.09019563 | 0.05893988 | 0.07352941 |
| Flax | 0.035477384 | 0.024852867 | 0.182756144 | 0.00544563 | 0.06146074 | 0.00785865 | 0.05882353 |
| Sheep Wool | 0.067895077 | 0.183374128 | 0.09534038 | 0.00726085 | 0.07548982 | 0.09430381 | 0.05882353 |
| Coir Fiber | 0.4042633 | 0.477403578 | 0.075191747 | 0.0635324 | 0.08170663 | 0.03367993 | 0.07352941 |
| Jute Fiber | 0.059949077 | 0.050190359 | 0.095087248 | 0.00544563 | 0.07467811 | 0.00962284 | 0.05882353 |
| Fibre glass | 0.047183985 | 0.064530968 | 0.259397991 | 0.00381194 | 0.0868133 | 0.23575954 | 0.17647059 |

**Step 8: Calculation of final weight in decision matrix**

Refer to the Table 4.36 in this section.

- In row 2, the normalized weight of each attribute is entered.
- In the corresponding rows the normalized weight of each material under different attributes is entered.
- Final weight is calculated by summing up the products of normalized weight of attributes and corresponding normalized weight of materials under each attribute.
- For example, to find the weight of Stone Wool, the following calculation is performed:

F126*F125+G126*G125+H126*H125+I126*I125+J126*J125+K126*K125+L126*L125

= 0.05620057

Here, row 125 is Normalized weight of attributes and row 126 is normalized weight of materials (used in equation 4.7) under those attributes as calculated from steps 4 and 6 . The capital letters denote the column for various attributes, as shown in Table 4.35 below:

**Table 4.35:** Key for final weight calculation formula.

| Column | Attribute |
|---|---|
| F | GWP |
| G | Embodied Energy |
| H | Bending stiffness |
| I | WVDRF |
| J | Thermal conductivity |
| K | Cost |
| L | Fire Class |

**Table 4.36:** Decision matrix.

| Attributes | GWP | Embodied Energy | Bending stiffness | WVDRF | Thermal conductivity | Cost | Fire Class | | Final Weight |
|---|---|---|---|---|---|---|---|---|---|
| Normalized weight | 0.216956826 | 0.195446341 | 0.161348394 | 0.14506305 | 0.11334346 | 0.09369285 | 0.07414908 | | |
| Stone Wool | 0.019508026 | 0.043173167 | 0.026837128 | 0.00417499 | 0.09513786 | 0.15717302 | 0.17647059 | | 0.05620057 |
| Expanded Polystyrene | 0.019284702 | 0.0242266 | 0.073508666 | 0.16336903 | 0.1006531 | 0.06735987 | 0.05882353 | | 0.06655948 |
| Polyurethane | 0.033816899 | 0.034452621 | 0.016099428 | 0.36304229 | 0.11201716 | 0.23575954 | 0.05882353 | | 0.10847919 |
| Polyisocyanurate | 0.01929594 | 0.012193699 | 0.006575199 | 0.37211835 | 0.15097965 | 0.04715191 | 0.14705882 | | 0.09404575 |
| Hemp Fibre | 0.280871643 | 0.064610831 | 0.115236916 | 0.00544563 | 0.070868 | 0.05239101 | 0.05882353 | | 0.11025102 |
| Kenaf | 0.012453967 | 0.021059624 | 0.053969154 | 0.00635324 | 0.09019563 | 0.05893988 | 0.07352941 | | 0.03764493 |
| Flax | 0.035477384 | 0.024852867 | 0.182756144 | 0.00544563 | 0.06146074 | 0.00785865 | 0.05882353 | | 0.05489602 |
| Sheep Wool | 0.067895077 | 0.183374128 | 0.09534038 | 0.00726085 | 0.07548982 | 0.09430381 | 0.05882353 | | 0.08875998 |
| Coir Fiber | 0.4042633 | 0.477403578 | 0.075191747 | 0.0635324 | 0.08170663 | 0.03367993 | 0.07352941 | | 0.22023136 |
| Jute Fiber | 0.059949077 | 0.050190359 | 0.095087248 | 0.00544563 | 0.07467811 | 0.00962284 | 0.05882353 | | 0.0526756 |
| Fibre glass | 0.047183985 | 0.064530968 | 0.259397991 | 0.00381194 | 0.0868133 | 0.23575954 | 0.17647059 | | 0.11026948 |

**Step 9: Preference Percentage**

- It is found by multiplying the final weight as found in previous step by 100.

**Table 4.37:** Decision matrix with preference percentage column.

| Attributes | GWP | Embodied Energy | Bending stiffness | WVDRF | Thermal conductivity | Cost | Fire Class | | Final Weight | | Preference % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Normalized weight | 0.216956826 | 0.195446341 | 0.161348394 | 0.14506305 | 0.11334346 | 0.09369285 | 0.07414908 | | | | |
| Stone Wool | 0.019508026 | 0.043173167 | 0.026837128 | 0.00417499 | 0.09513786 | 0.15717302 | 0.17647059 | | 0.05620057 | 100 | 5.62005749 |
| Expanded Polystyrene | 0.019284702 | 0.0242266 | 0.073508666 | 0.16336903 | 0.1006531 | 0.06735987 | 0.05882353 | | 0.06655948 | 100 | 6.65594825 |
| Polyurethane | 0.033816899 | 0.034452621 | 0.016099428 | 0.36304229 | 0.11201716 | 0.23575954 | 0.05882353 | | 0.10847919 | 100 | 10.8479191 |
| Polyisocyanurate | 0.01929594 | 0.012193699 | 0.006575199 | 0.37211835 | 0.15097965 | 0.04715191 | 0.14705882 | | 0.09404575 | 100 | 9.40457502 |
| Hemp Fibre | 0.280871643 | 0.064610831 | 0.115236916 | 0.00544563 | 0.070868 | 0.05239101 | 0.05882353 | | 0.11025102 | 100 | 11.025102 |
| Kenaf | 0.012453967 | 0.021059624 | 0.053969154 | 0.00635324 | 0.09019563 | 0.05893988 | 0.07352941 | | 0.03764493 | 100 | 3.76449253 |
| Flax | 0.035477384 | 0.024852867 | 0.182756144 | 0.00544563 | 0.06146074 | 0.00785865 | 0.05882353 | | 0.05489602 | 100 | 5.48960164 |
| Sheep Wool | 0.067895077 | 0.183374128 | 0.09534038 | 0.00726085 | 0.07548982 | 0.09430381 | 0.05882353 | | 0.08875998 | 100 | 8.87599816 |
| Coir Fiber | 0.4042633 | 0.477403578 | 0.075191747 | 0.0635324 | 0.08170663 | 0.03367993 | 0.07352941 | | 0.22023136 | 100 | 22.0231356 |
| Jute Fiber | 0.059949077 | 0.050190359 | 0.095087248 | 0.00544563 | 0.07467811 | 0.00962284 | 0.05882353 | | 0.0526756 | 100 | 5.26755951 |
| Fibre glass | 0.047183985 | 0.064530968 | 0.259397991 | 0.00381194 | 0.0868133 | 0.23575954 | 0.17647059 | | 0.11026948 | 100 | 11.0269484 |

- The graph in fig 4.17 represents the preference of materials arising from the AHP process in a more compelling manner.

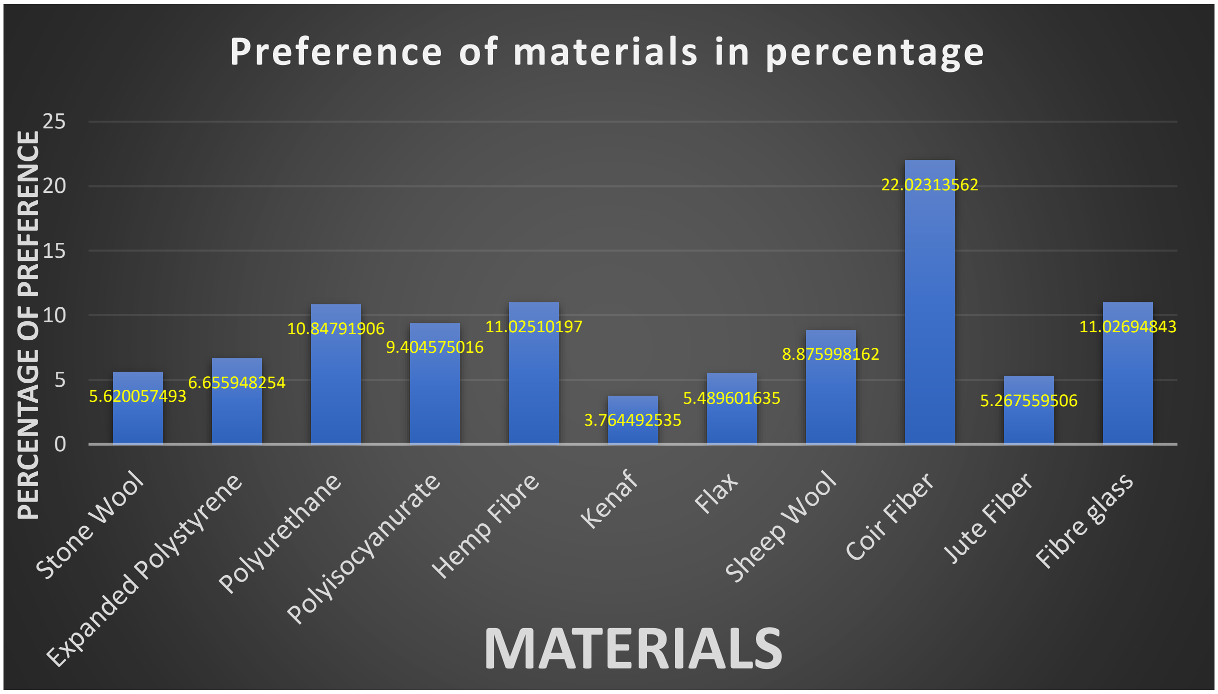


**Figure 4.17:** Preference of materials in percentage.

**4.13 Result**

Based on our analysis and calculations using Analytical Hierarchal Process (AHP), Coir fiber is the most preferred material (with preference rating of 22.02%) followed by Fiber glass and hemp fiber with 11.02% preference rating each. It is worth noting that two of the top three materials are natural fibers. Kenaf is the least preferred material with preference rating of 3.76%.

Table 4.38 represents preference percentage of alternative insulation materials in descending order:

**Table 4.38:** Preference percentage of alternative insulation materials in descending order.

| Order of Preference | Preference percentage |
|---|---|
| Coir | 22.023 |
| Fiberglass | 11.027 |
| Hemp Fiber | 11.025 |
| Polyurethane | 10.848 |
| Polyisocyanurate | 9.405 |
| Sheep wool | 8.876 |
| Expanded Polystyrene | 6.656 |
| Stone Wool | 5.620 |
| Flax | 5.490 |
| Jute Fiber | 5.268 |
| Kenaf | 3.764 |

### 4.14 Best Alternative Insulation Material

The insulation material industry for buildings is currently dominated by synthetic materials like expanded polystyrene, fiberglass, and stone wool. Although from this research natural fibers like coir and hemp fibers, have significantly better overall performance and should be considered as replacement for other synthetic insulation materials. Table 4.39 (Reference case) shows by choosing coir fiber over fiberglass, we save on embodied energy by more than 1400 $MJ_{eq}$ and GWP by 63 Kg $CO_2$ eq.

**Table 4.39:** GWP and embodied energy for reference case in two materials.

| Material | Embodied energy of 1 F.U. (kg) | Total Embodied energy of material ($MJ_{eq}$) | GWP per f.u. (kg $CO_2$ eq) | Total GWP (kg $CO_2$ eq) |
|---|---|---|---|---|
| Coir Fiber | 14.75 | 222.789369 | 0.55 | 8.3074002 |
| Fiberglass | 229.02 | 1648.207747 | 9.89 | 71.17620563 |

Let us see what happens if we plan to reduce the energy consumption by 30% (Case 2). Thus, the new energy consumption would be 7,176,840.923 BTUs. This would require an R-Value of 2.41, increasing the thickness and the weight of the materials. This would also increase the GWP and embodied energy associated insulation materials Table 4.40 shows what the GWP and Embodied Energy data would look like. The increase in embodied energy savings from reducing energy consumption by 30% and switching to coir fiber is close to 2088 $MJ_{eq}$. and GWP savings is around 95 Kg $CO_2$ eq. Similarly, as the Table 4.41 shows, the increase in embodied energy savings from reducing energy consumption by 50% (Case 3) and switching to coir fiber is close to 3000 $MJ_{eq}$. and GWP savings is more than 130 Kg $CO_2$ eq. A comparison of these two cases with the reference case is made in Table 4.42.

**Table 4.40:** GWP and embodied energy for 30% reduced energy use case in two materials.

| Material | Embodied energy of 1 F.U. (kg) | Total Embodied energy of material ($MJ_{eq}$) | GWP per f.u. (kg CO2 eq) | Total GWP (kg CO2 eq) | R value |
|---|---|---|---|---|---|
| Coir Fiber | 14.75 | 326.3140913 | 0.55 | 12.16764408 | 2.416714285 |
| Fiberglass | 229.02 | 2414.089216 | 9.89 | 104.2500321 | 2.416714285 |

**Table 4.41:** GWP and embodied energy for 50% reduced energy use case in two materials.

| Material | Embodied energy of 1 F.U. (kg) | Total Embodied energy of material ($MJ_{eq}$) | GWP per f.u. (kg CO2 eq) | Total GWP (kg CO2 eq) | R value |
|---|---|---|---|---|---|
| Coir Fiber | 14.75 | 464.3470545 | 0.55 | 17.31463593 | 3.438999999 |
| Fiberglass | 229.02 | 3435.264509 | 9.89 | 148.3484673 | 3.438999999 |

**Table 4.42:** GWP and embodied energy comparison of 3 cases.

| Case | Total Embodied energy (Mjeq) savings | Total GWP (kg CO2 eq) savings |
|---|---|---|
| **1**. Reference | 1425.418378 | 62.86880543 |
| **2.** 30% less energy consumption | 2087.775124 | 92.08238799 |
| **3.** 50% less energy consumption | 2970.917454 | 131.0338314 |

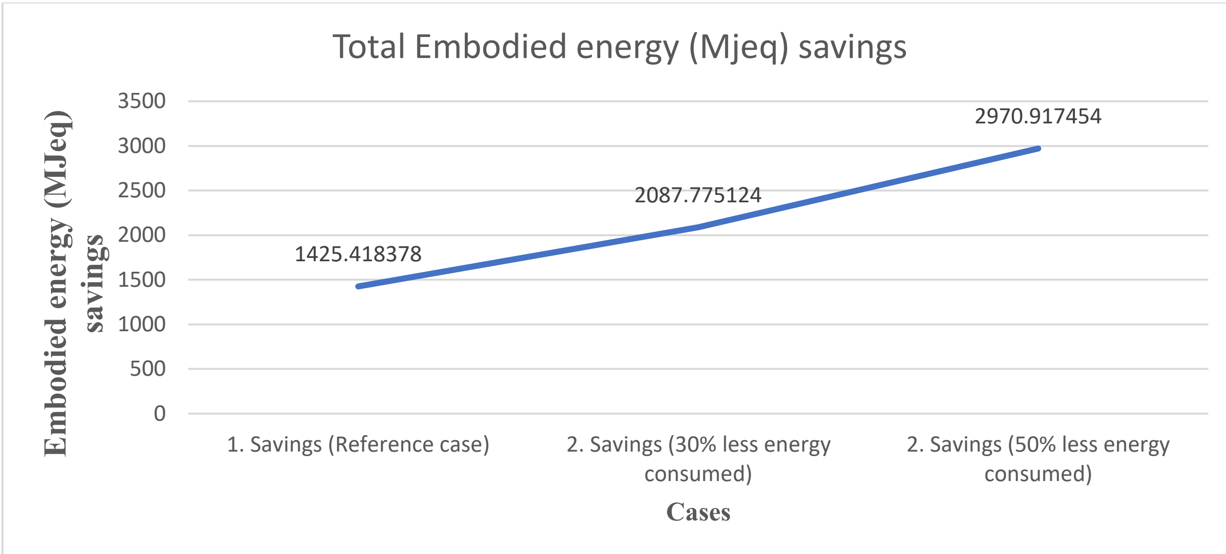


**Figure 4.18:** Total embodied energy savings when coir is selected.

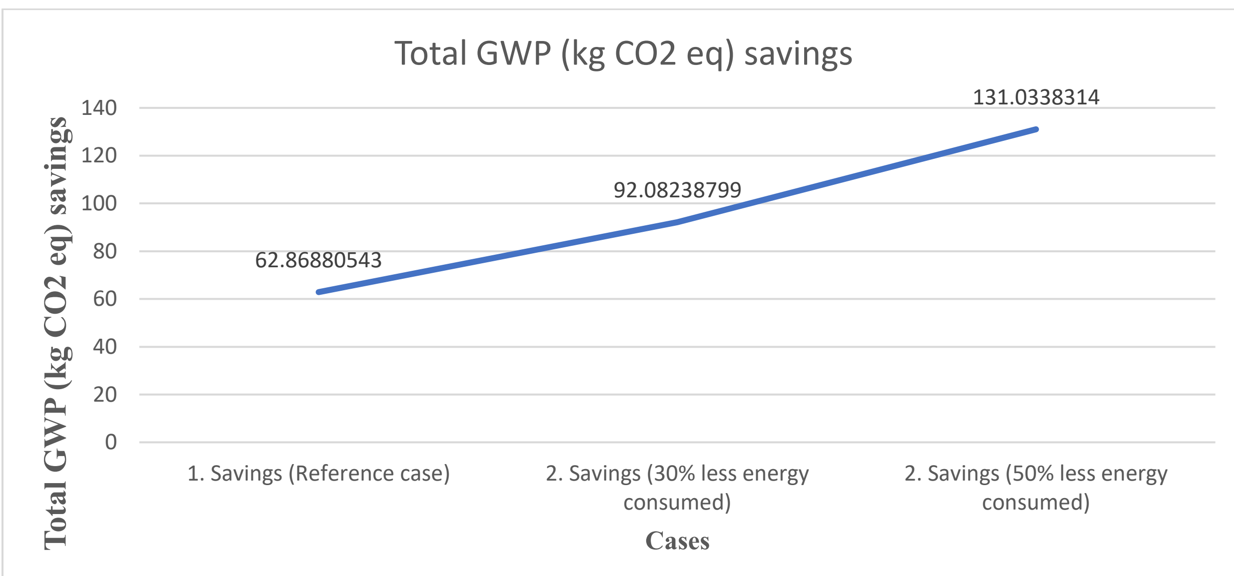


**Figure 4.19:** Total kg $CO_2$ savings when coir is selected.

Figures 4.18 and 4.19 clearly show that savings in both embodied energy and GWP increases when coir fiber is selected as the insulation material.

This research proposes that coir fiber dominates its counterparts in both the significant factors i.e., GWP and embodied energy. This makes it the most preferred choice of insulation material with a preference percentage of 22%. Although, there is one important attribute in which this natural fiber underperforms which is cost. Unfortunately, cost is one of the most important considerations that companies are concerned with and efforts are required to bring this down.

### 4.15 Coir Fiber

### 4.15.1 What is Coir Fiber?

Obtained from the husk of coconuts, this natural fiber is a mere byproduct of the coconut industry. It is one of the most promising fibers on the list due to high mechanical strength, remains unaffected by rodents and insects, and fire-retardant properties can be easily added. The only major drawback is energy consumed in transportation because it is mainly available in the regions surrounding, India, Sri Lanka and Indonesia. Figure 4.20 illustrates the coconut producing countries.

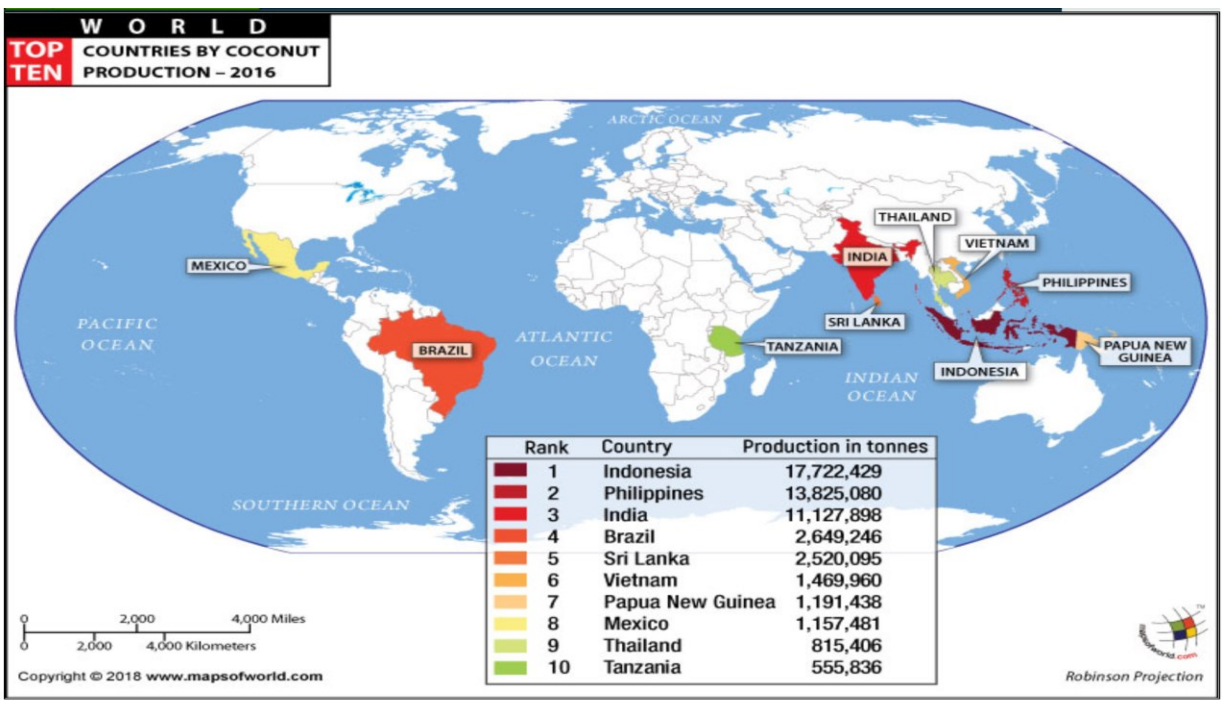


**Figure 4.20:** Coconut producing countries [56].

Figure 4.21 shows from which part of Coconut is coir obtained.

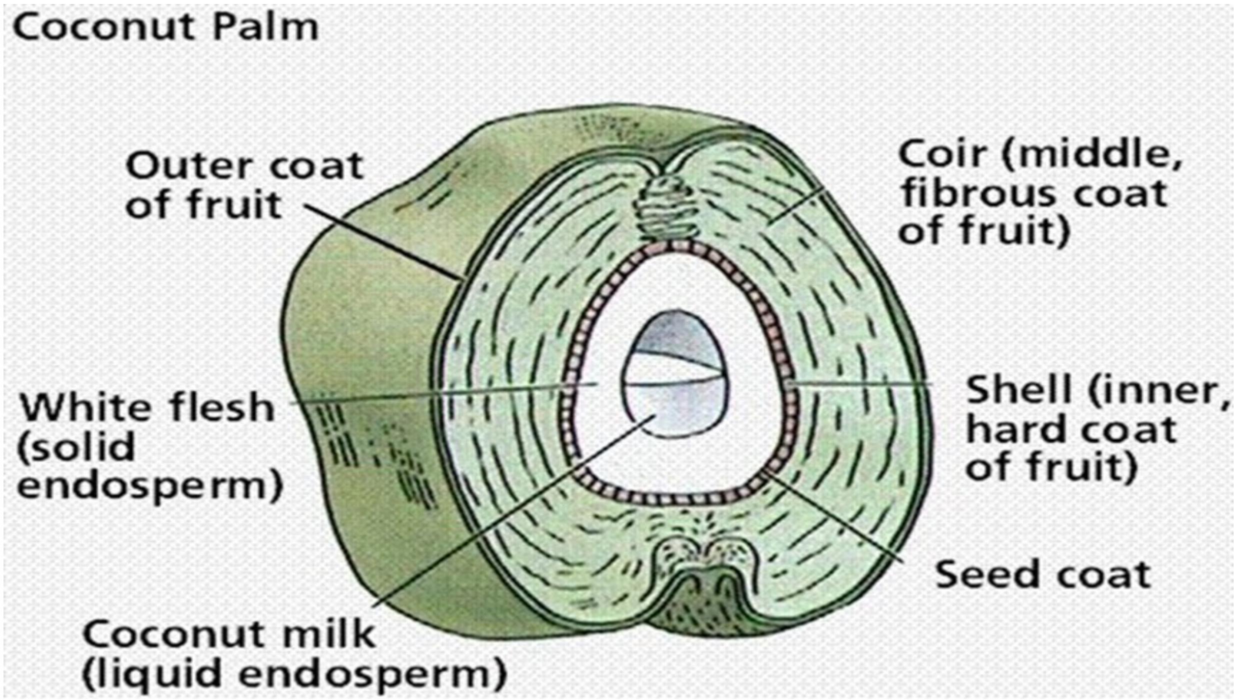


**Figure 4.21:** Diagram for parts of coconut [57].

As seen in the Figure 4.21, coir is the middle fibrous coat of Coconut. It is sandwiched between the outer coat of the fruit and the seed coat. The coir obtained can be of two kinds:

- Brown fiber: When coir is obtained from the ripe Coconut. They are comparatively stronger and are resistant to abrasion.
- White fiber: When coir is obtained from the raw Coconut. They are tender and weaker than the brown ones. They are smooth and have soft and fine feel characteristics.

**4.15.2 Manufacturing Process of Coir Fiber**

The process of manufacturing coir fiber is not very advanced. It is prevalent in countries like Indonesia, Philippines and India. There is no standardized method, and the process uses a combination of some basic machines and manual labor. Here is a high-level view of the steps involved [58]:

- Harvesting: Coconuts have different physical properties at different stages in life. Depending upon what is being manufactured Coconuts are harvested. The insulation fiber manufacturers use the ripe fallen Coconuts and sometimes the raw ones from the tree.

- Husking: It involves separating the coconut fiber from the sturdy husked fruit. Generally, a sharp tipped metallic tool is used by labors to carry out the process. When raw coconut is sent to the husking process, it is stored for a month, laid out on the floor, before being husked.
- Retting: It is done to soften the layers of coconut by decomposing the husk's pulp using chemicals or water. After decomposition, it becomes easier for the coir pith to separate from coir fiber. For the raw coconut, saline water retting is done and for ripe coconuts fresh water is used.
- Defibering: After the process of retting some pulp is extracted and this is beaten up to defiber the fiber and the pith. It can be manually done by mallets or rotating machines can be used. At the end of this stage, the obtained product is cleaned up and ready to be made into different products. For making insulation boards for buildings, it is mixed with resins and made into panels.

### 4.15.3 Advantages of Using Coir Fiber [57]

- Of all the natural fibers, it has best toughness.
- It is resistant to insects, fungi and decay.
- The production of fiber is a basic mechanical process, so sophisticated equipment is no required.
- The production is not energy intensive.
- It is very eco-friendly.

### 4.15.4 Drawbacks of Using Coir Fiber [59]

- It is produced in countries where heating insulation requirement is not much. Thus, there is a lot of cost and GWP associated with transport of coir fibers.
- Although not energy intensive, but the process is very labor intensive and safe working condition of labors must be ensured.
- There is tremendous value addition in each step of the processing of the coir fiber.

Table 4.43 gives a rough estimate of costs in each step of the processing.

**Table 4.43:** Cost estimate for 100 kg of coir fiber manufacturing process.

| **Process** | **Cost in Rs** | **Cost in $** |
|---|---|---|
| Harvest | 130 | 1.805555556 |
| Transport to processing facility | 200 | 2.777777778 |
| Storage and processing at facility | 200 | 2.777777778 |
| Labor charges | 150 | 2.083333333 |
| Making insulation panels from fibers using resins and additives | 120 | 1.666666667 |
| Packaging | 100 | 1.388888889 |
| Shipping to installation venue | 400 | 5.555555556 |
| **Total** | **1300** | **18.05555556** |

The first column in Table 4.43 represents the cost involved in each step. Clearly, transportation and shipping charges makeup for the majority and that is a major drawback. The second column is cost in Rupees (Currency of India). An approximate value in Dollars is found by dividing Rupees with 72. Thus, we can see that from the first stage to the last stage, i.e., from harvest to shipping, the value of coir fiber increases 10 times [60]. This is very high and extremely negative for promotion of coir fiber as an alternative to other synthetic insulation materials.

# CHAPTER 5
# CONCLUSIONS

After careful consideration on various attributes and alternatives and by using AHP decision making tool, this thesis finds that coir fiber is the best insulation material for buildings in Chicago. Simulation was performed for data using weather file for city of Chicago. Out of eleven materials considered, coir, a natural fiber, performs better than fiberglass, the best performing synthetic fiber, and hemp, another natural fiber, performs almost equal to fiberglass. All the natural fibers except Kenaf, perform well in GWP and Embodied energy categories when compared to synthetic fibers. The reason why the top two natural fibers outperform synthetic fibers is because of 40 % influence of GWP and Embodied energy on the final decision. Coir fiber has best rating in GWP and Embodied energy by some margin and does well in other attributes so takes top spot in our list. This is closely followed by Hemp fiber which also performs well in the significant attributes. Although Kenaf, a natural fiber, is the last preferred material, because from the available data it has high Embodied energy and GWP. Fiberglass is the best performing synthetic fiber because it does well in all the attributes and especially the two significant decision influencing factors. Fiberglass is also cost effective and has excellent bending stiffness and fire-resistant properties.

Let us have a look at what can happen if we build 1000 shoebox model houses. The area of the model used for our calculations is $64m^2$ approximately and kilogram equivalent of $CO_2$ forgone if we use coir instead of fiberglass 63 kg eq. of $CO_2$ (Table 4.42). For 1000 such house savings is worth 63,000 kg eq. of $CO_2$.

This translates to the following data [61].

- GHG emissions from a passenger car driven for 156,000 miles every year saved.
- Emissions saved equivalent to approximately 6200 gallons of diesel consumed.
- GHGs not emitted worth 70,000 pounds of burning coal

## APPENDICES

## APPENDIX A

### 1. World energy production, consumption and emission trends

**Table A.1:** World energy production, consumption, and emission trends.

| Year | Production (Quad BTU) | Consumption (BTU) | Emissions (mmt of $CO_2$) |
|---|---|---|---|
| 1980 | 294.7483841 | 293.4628211 | 18746.26769 |
| 1981 | 289.4317471 | 290.8667602 | 18453.95668 |
| 1982 | 288.4748796 | 291.3595724 | 18429.5732 |
| 1983 | 291.4191914 | 295.1058344 | 18590.52702 |
| 1984 | 307.6024749 | 308.8534318 | 19955.74533 |
| 1985 | 315.0934438 | 317.4346791 | 20409.59498 |
| 1986 | 325.3370381 | 324.5443526 | 20938.65381 |
| 1987 | 333.0209682 | 334.6049632 | 21541.03526 |
| 1988 | 345.9434362 | 347.6473115 | 22256.63424 |
| 1989 | 352.6734139 | 352.3714686 | 22470.94249 |
| 1990 | 358.4595891 | 358.9981006 | 22916.70516 |
| 1991 | 353.2670883 | 352.3677631 | 22079.9125 |
| 1992 | 352.1748409 | 351.1549835 | 21875.22217 |

| | | | |
|---|---|---|---|
| 1993 | 353.1332657 | 354.0552263 | 22011.6795 |
| 1994 | 359.2252481 | 358.0027646 | 22209.60834 |
| 1995 | 367.0392724 | 367.9691123 | 22736.13907 |
| 1996 | 376.3142218 | 377.7273635 | 23216.22538 |
| 1997 | 380.8683181 | 378.9048553 | 23318.74591 |
| 1998 | 385.5176177 | 381.492854 | 23400.81136 |
| 1999 | 385.4673501 | 389.494706 | 23814.72915 |
| 2000 | 398.9085864 | 402.4398245 | 24597.05958 |
| 2001 | 404.666233 | 405.9631394 | 24849.74045 |
| 2002 | 406.4441863 | 414.8844333 | 25419.42903 |
| 2003 | 422.2821323 | 430.0350652 | 26639.382 |
| 2004 | 444.5438266 | 450.5077802 | 27915.90645 |
| 2005 | 460.442251 | 465.4175475 | 29047.9911 |
| 2006 | 472.4646685 | 480.2211772 | 30025.7188 |
| 2007 | 481.0509233 | 493.3083602 | 30390.35317 |
| 2008 | 494.0235392 | 499.8868668 | 31154.13594 |
| 2009 | 492.2191581 | 494.445766 | 30922.13525 |
| 2010 | 518.2903787 | 523.8638248 | 32718.44968 |
| 2011 | 533.989931 | 538.8190625 | 34031.43804 |
| 2012 | 547.3380081 | 550.9401688 | 34859.78875 |
| 2013 | 554.8632617 | 561.8117164 | 35556.80052 |
| 2014 | 564.729499 | 567.0367069 | 35622.40124 |
| 2015 | 569.0972968 | 570.0746552 | 35667.28897 |
| 2016 | 564.6939296 | 573.9973998 | 35677.28591 |
| 2017 | 576.8678523 | 583.5666381 | 36060.85927 |

## 2. USA Energy Trends:

**Table A.2:** USA energy production, consumption, and emission trends.

| Year | Production(Quad BTU) | Consumption (Quad BTU) | Emissions (mmt of $CO_2$) |
|---|---|---|---|
| 1980 | 67.14544307 | 78.02111311 | 4750.675 |
| 1981 | 66.90950804 | 76.05718694 | 4627.751 |
| 1982 | 66.52673229 | 73.04618866 | 4393.721 |
| 1983 | 64.06633267 | 72.91539428 | 4367.856 |
| 1984 | 68.79958614 | 76.5706968 | 4595.502 |
| 1985 | 67.66130021 | 76.3341345 | 4586.301 |
| 1986 | 67.03025577 | 76.59888807 | 4597.353 |
| 1987 | 67.50638343 | 79.00820267 | 4755.297 |
| 1988 | 68.88957904 | 82.65916904 | 4979.453 |
| 1989 | 69.28452194 | 84.73999296 | 5066.674 |
| 1990 | 70.66756098 | 84.4328603 | 5038.776 |
| 1991 | 70.3210655 | 84.38030008 | 4993.74 |
| 1992 | 69.91444308 | 85.72488506 | 5091.722 |
| 1993 | 68.27267781 | 87.26588762 | 5182.609 |
| 1994 | 70.68306405 | 88.98323406 | 5259.91 |
| 1995 | 71.12913993 | 90.93070401 | 5322.488 |
| 1996 | 72.43522134 | 93.93451089 | 5510.158 |
| 1997 | 72.42008517 | 94.50699934 | 5581.044 |
| 1998 | 72.8264613 | 94.92018984 | 5634.331 |
| 1999 | 71.68564056 | 96.54452444 | 5689.163 |

| | | | |
|---|---|---|---|
| 2000 | 71.27059025 | 98.70222416 | 5861.952 |
| 2001 | 71.67537099 | 96.06373375 | 5760.367 |
| 2002 | 70.65304163 | 97.53539089 | 5801.793 |
| 2003 | 69.8846722 | 97.83477319 | 5851.851 |
| 2004 | 70.16946438 | 100.0023681 | 5971.307 |
| 2005 | 69.37692262 | 100.1015762 | 5991.351 |
| 2006 | 70.67757674 | 99.39154056 | 5910.783 |
| 2007 | 71.33806878 | 100.8933632 | 6001.149 |
| 2008 | 73.14488954 | 98.75371116 | 5811.604 |
| 2009 | 72.59170139 | 93.94221562 | 5387.393 |
| 2010 | 74.90719767 | 97.51685893 | 5585.596 |
| 2011 | 78.08167918 | 96.85023039 | 5446.359 |
| 2012 | 79.23400096 | 94.38012321 | 5236.945 |
| 2013 | 81.83652416 | 97.11729191 | 5362.523 |
| 2014 | 87.71461843 | 98.27567333 | 5413.51 |
| 2015 | 88.25022874 | 97.37785199 | 5267.066 |
| 2016 | 84.2688786 | 97.32866214 | 5174.793 |
| 2017 | 88.14861128 | 97.60292603 | 5133.437 |

**3. Case study of China:**

The table below illustrates energy production, consumption, and emissions from China in a period between 1980 and 2017.

**Table A.3:** China energy production, consumption, and emission trends.

| Year | Production (Quadrillion BTU) | Consumption (BTU) | Emissions (mn metric tonnes $CO_2$) |
|---|---|---|---|
| 1980 | 19.5398192 | 19.82671694 | 1664.569001 |
| 1981 | 19.35768401 | 19.60988173 | 1648.030815 |
| 1982 | 20.43655564 | 20.36301423 | 1710.955585 |
| 1983 | 21.85858006 | 21.5537735 | 1810.848455 |
| 1984 | 23.91875739 | 23.22236109 | 1963.509575 |
| 1985 | 26.28375633 | 24.30058358 | 2059.549126 |
| 1986 | 27.06785294 | 24.96700547 | 2132.60389 |
| 1987 | 28.04417655 | 26.33932961 | 2254.60119 |
| 1988 | 29.3773539 | 28.14206907 | 2401.885181 |
| 1989 | 31.19737806 | 28.19915178 | 2397.017623 |
| 1990 | 31.87634165 | 31.05258606 | 2666.577917 |
| 1991 | 32.12976319 | 28.57557533 | 2441.592651 |
| 1992 | 32.90956647 | 29.93062743 | 2522.473762 |
| 1993 | 34.05030512 | 32.270316 | 2716.804564 |
| 1994 | 36.21409428 | 34.69763497 | 2902.1495 |
| 1995 | 37.95601204 | 37.4182711 | 3130.023976 |
| 1996 | 40.03036502 | 39.1965528 | 3222.867326 |
| 1997 | 39.42379399 | 37.23441859 | 3122.092591 |

| | | | |
|---|---|---|---|
| 1998 | 39.05907716 | 38.29867543 | 3115.703184 |
| 1999 | 38.82117585 | 40.17492922 | 3269.73685 |
| 2000 | 41.26209772 | 42.93761768 | 3523.152294 |
| 2001 | 44.01147682 | 45.47011579 | 3694.868005 |
| 2002 | 46.20334763 | 48.86918772 | 3960.514426 |
| 2003 | 52.76464665 | 56.97263029 | 4625.453089 |
| 2004 | 60.32643526 | 66.4384717 | 5375.481015 |
| 2005 | 66.78072786 | 74.5729564 | 6105.598124 |
| 2006 | 72.1873463 | 82.43537198 | 6739.961197 |
| 2007 | 77.52240235 | 88.79435068 | 7043.430704 |
| 2008 | 82.35218488 | 92.91918384 | 7496.677218 |
| 2009 | 87.79845676 | 100.4284226 | 8188.765191 |
| 2010 | 97.03202164 | 109.3580724 | 8779.189764 |
| 2011 | 104.9462269 | 120.8220432 | 9832.278194 |
| 2012 | 110.9875871 | 129.406108 | 10362.2039 |
| 2013 | 113.4030268 | 135.0366555 | 10801.77342 |
| 2014 | 114.7911783 | 136.8982495 | 10701.49609 |
| 2015 | 114.2979763 | 137.2783265 | 10508.33041 |
| 2016 | 107.11639 | 137.4165048 | 10501.79834 |
| 2017 | 112.0184074 | 139.4347333 | 10486.98119 |

**4. Case study of India:**

The table below illustrates energy production, consumption and emissions from India in a period between 1980 and 2017.

**Table A.4:** India energy production, consumption and emission trends.

| Year | Production (Quadrillion BTU) | Consumption (BTU) | Emissions (mn metric tonnes $CO_2$) |
|---|---|---|---|
| 1980 | 2.830489893 | 3.751134576 | 271.4666483 |
| 1981 | 3.34936428 | 4.206786617 | 306.8298353 |
| 1982 | 3.61376955 | 4.363656686 | 322.5903457 |
| 1983 | 3.974146359 | 4.629071264 | 341.6840369 |
| 1984 | 4.276300547 | 4.977342588 | 367.636716 |
| 1985 | 4.590215843 | 5.255762258 | 391.3892885 |
| 1986 | 4.933846709 | 5.657328549 | 417.3678514 |
| 1987 | 5.114447405 | 5.964408477 | 449.983083 |
| 1988 | 5.650552657 | 6.600253648 | 488.8661039 |
| 1989 | 5.911336545 | 6.960810397 | 515.3737429 |
| 1990 | 6.157093501 | 7.460755176 | 548.6420913 |
| 1991 | 6.537897031 | 7.857381735 | 581.0544595 |
| 1992 | 6.593519717 | 8.278263008 | 617.7329194 |
| 1993 | 6.814673616 | 8.62637611 | 646.9273924 |
| 1994 | 7.31259098 | 9.26800549 | 689.7085451 |
| 1995 | 7.734916382 | 9.876121666 | 745.8068105 |
| 1996 | 7.988100588 | 10.32691469 | 782.663781 |
| 1997 | 8.335636496 | 10.8456512 | 818.9532965 |

| | | | |
|---|---|---|---|
| 1998 | 8.476570373 | 11.00625267 | 839.4844542 |
| 1999 | 8.541195015 | 11.73475996 | 884.6787127 |
| 2000 | 8.656288785 | 12.56505519 | 922.5630728 |
| 2001 | 8.950263918 | 12.79674127 | 945.9646993 |
| 2002 | 9.398062347 | 13.39337945 | 993.9317024 |
| 2003 | 9.926490515 | 13.88789515 | 1014.048347 |
| 2004 | 10.47207201 | 15.09675772 | 1119.956412 |
| 2005 | 11.07475211 | 15.93693808 | 1169.398363 |
| 2006 | 11.70478685 | 17.2070854 | 1259.360552 |
| 2007 | 12.30413259 | 18.63329334 | 1368.379923 |
| 2008 | 12.34453857 | 19.13197983 | 1411.06133 |
| 2009 | 12.70767768 | 20.22608682 | 1497.486494 |
| 2010 | 13.85786805 | 21.69790702 | 1604.543494 |
| 2011 | 14.27764462 | 22.81170341 | 1677.352792 |
| 2012 | 15.27292206 | 25.10523359 | 1905.228814 |
| 2013 | 15.16386773 | 25.70778491 | 1944.444972 |
| 2014 | 15.7290778 | 27.3079453 | 2092.365758 |
| 2015 | 16.14662367 | 28.37694192 | 2177.981892 |
| 2016 | 17.12257088 | 29.47808804 | 2237.148562 |
| 2017 | 17.67588748 | 30.47634011 | 2312.061219 |

6. The table below shows years, emissions, and emission growth rate to project control chart.

**Table A.5:** Years, emissions, and emission growth rate to project control chart.

| Year | Emissions (mn metric tonnes $CO_2$) | Emission Growth (in %) |
|---|---|---|
| 1980 | 18746.26769 | 0 |
| 1981 | 18453.95668 | -1.559302413 |
| 1982 | 18429.5732 | -0.13213146 |
| 1983 | 18590.52702 | 0.87334533 |
| 1984 | 19955.74533 | 7.343623511 |
| 1985 | 20409.59498 | 2.274280647 |
| 1986 | 20938.65381 | 2.592206407 |
| 1987 | 21541.03526 | 2.876887192 |
| 1988 | 22256.63424 | 3.322026847 |
| 1989 | 22470.94249 | 0.962896041 |
| 1990 | 22916.70516 | 1.98372931 |
| 1991 | 22079.9125 | -3.651452757 |
| 1992 | 21875.22217 | -0.927043186 |
| 1993 | 22011.6795 | 0.623798571 |
| 1994 | 22209.60834 | 0.899199179 |
| 1995 | 22736.13907 | 2.370733994 |
| 1996 | 23216.22538 | 2.111556002 |
| 1997 | 23318.74591 | 0.441589984 |
| 1998 | 23400.81136 | 0.351929089 |
| 1999 | 23814.72915 | 1.768818118 |

| | | |
|---|---|---|
| 2000 | 24597.05958 | 3.285069602 |
| 2001 | 24849.74045 | 1.027280826 |
| 2002 | 25419.42903 | 2.292533325 |
| 2003 | 26639.382 | 4.799293358 |
| 2004 | 27915.90645 | 4.791869594 |
| 2005 | 29047.9911 | 4.055339025 |
| 2006 | 30025.7188 | 3.365904714 |
| 2007 | 30390.35317 | 1.214406804 |
| 2008 | 31154.13594 | 2.513240825 |
| 2009 | 30922.13525 | -0.744686642 |
| 2010 | 32718.44968 | 5.809153915 |
| 2011 | 34031.43804 | 4.012990757 |
| 2012 | 34859.78875 | 2.43407496 |
| 2013 | 35556.80052 | 1.999472152 |
| 2014 | 35622.40124 | 0.184495573 |
| 2015 | 35667.28897 | 0.126009825 |
| 2016 | 35677.28591 | 0.028028313 |
| 2017 | 36060.85927 | 1.075119227 |

## APPENDIX B

**Energy simulation with fiberglass insulation**

Step 1: Open the EnergyPlus software and load the shoebox model in the input file. Then select the weather file which for our case is Chicago. (The weather data for city of Chicago is readily available in the software.) Then click on Edit-IDF Editor push button.

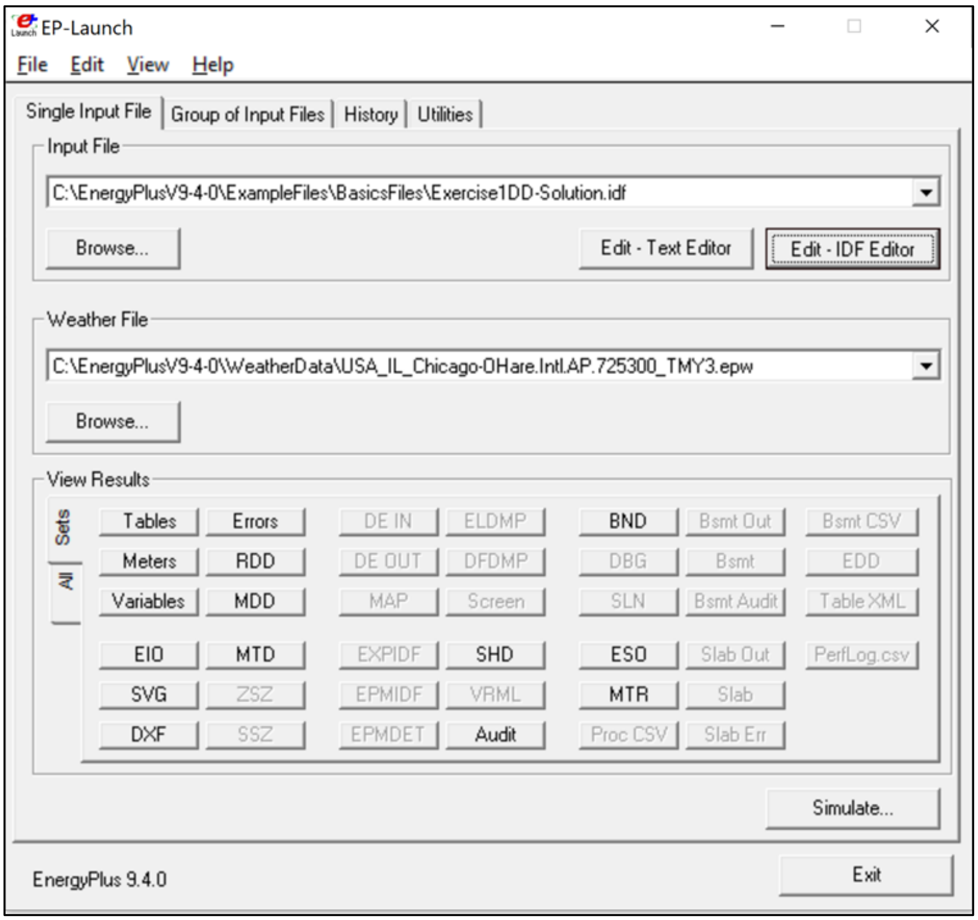


**Figure B.1:** Loading input and weather files.

Step 2:

Now we will select the type of insulation material we want to use in our simulation. For that we will go to the class list and select the desired material. We can also create a material of our own by declaring the values of certain properties like density, conductivity, specific heat, etc.

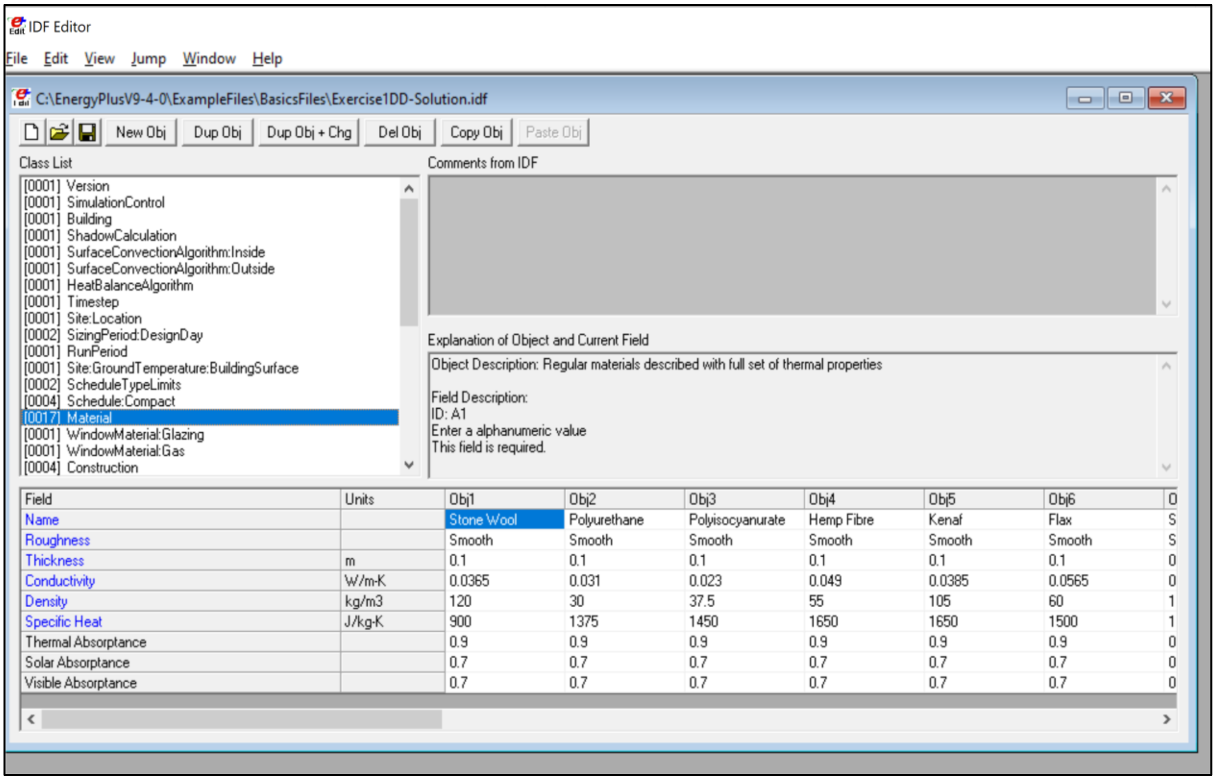


**Figure B.2:** Input of material data.

Step 3:

After declaring the properties of material, we want to use in the Material domain, we wish to set a configuration for the type of wall. The wall composition can be of multiple layers, but for our purpose we have a three-layered wall. The outermost layer made of wood siding, the middle later made if Fiberglass or the desired insulation material and the innermost layer made of plasterboard. In the fig below, Object 2 is the wall of the model. We can continue to add new layers to the wall to change its configuration.

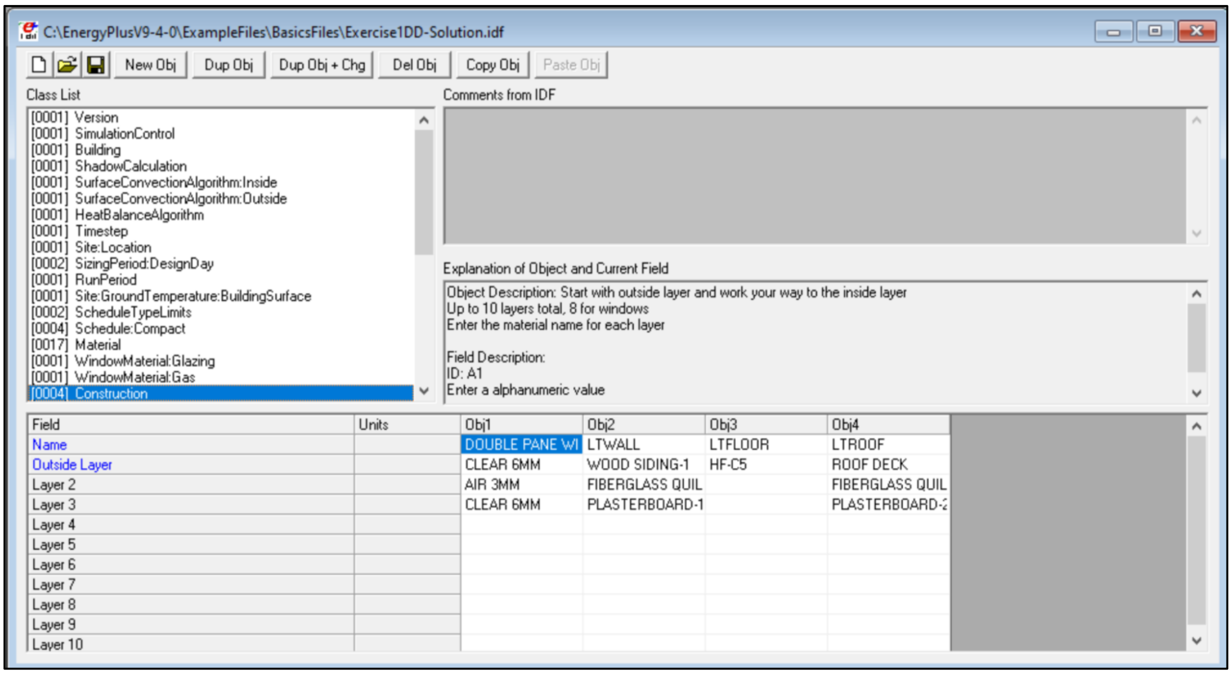


**Figure B.3:** Designing the wall layers.

Step 4:

Once the desired materials and configuration of the walls are declared, we are ready for simulation of the model. We will return to the EP-Launch dialog box and press the simulate key.

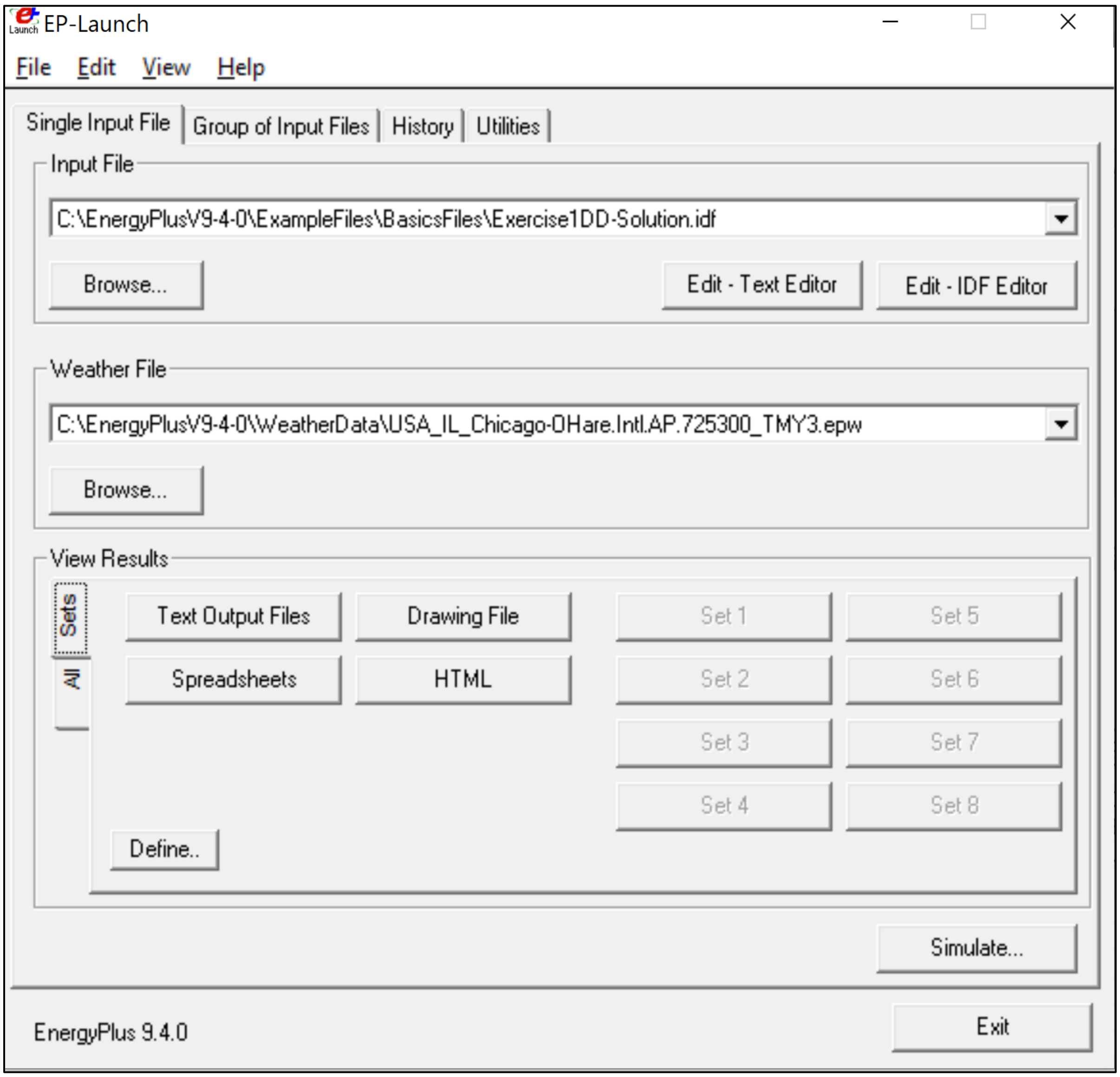


**Figure B.4:** Simulating the model.

This will yield the following results.

Report: **Annual Building Utility Performance Summary**

For: **Entire Facility**

Timestamp: **2021-01-28 21:47:54**

**Values gathered over 8760.00 hours**

**Site and Source Energy**

| | Total Energy [GJ] | Energy Per Total Building Area [MJ/m2] | Energy Per Conditioned Building Area [MJ/m2] |
|---|---|---|---|
| Total Site Energy | 29.03 | 604.81 | 604.81 |
| Net Site Energy | 29.03 | 604.81 | 604.81 |
| Total Source Energy | 86.44 | 1800.89 | 1800.89 |
| Net Source Energy | 86.44 | 1800.89 | 1800.89 |

**Figure B.5:** Result of simulation.

### 4.9 Results

The dialog box above shows the annual utility performance of our shoebox model for the year 2021. The total source energy per conditioned area is 1800.89 $MJ/m^2$. We are particularly interested in the total site energy because that gives the true picture of greenhouse gases released in the environment. The other factor total site energy does not consider the total energy initially produced at source but only the amount used by the site. This does not account for energy losses during distribution or due to other factors. It should be kept in mind that energy lost was also a contributor to released emissions.

## REFERENCES


1. A. Tooze, and P. Warde, 2005. A long run historical perspective on the prospects for uncoupling economic growth and CO2 emissions. Submission to Stern Review, December 2005. https://webarchive.nationalarchives.gov.uk/+/http://www.hm-treasury.gov.uk/media/2/1/climatechange_drjatooze_1.pdf

2. V. Smil,“Preindustrial prime movers and fuels,” in Energy in World History. Boulder, CO, USA: Westview Press, 1994, pp. 92-156

3. A. G. Arnold,“Development of a method for recording energy costs and uses during the construction process,” Ph.D. dissertation, Dept. of Architecture, Texas A&M University, College Station, Texas , 2008.

4. M. Roser, H. Ritchie, and E. Oritz-Ospina,“World Population Growth,” Ourworldindata.org https://ourworldindata.org/world-population-growth [Accessed March 2021].

5. K. Roberts,“The Evolution of Energy Sources: A visual Timeline,” [online]. Available: https://www.switchmybusiness.com/resources/the-evolution-of-energy-sources-a-visual-timeline/ [Accessed March 2021].

6. U.S. Energy Information Administration,“Glossary: Primary Energy Consumption,” EIA Independent& Analysis Statistics U.S. Energy Information [online]. Available: https://www.eia.gov/tools/glossary/index.php?id=Primary%20energy%20consumption [Accessed March 2021].

7. H. Ritchie and Max,“Emissions by Sector,” August 2020. [Online]. Available: https://ourworldindata.org/emissions-by-sector [Accessed March 2021].

8. U.S. Energy Information Administration,“Total Energy,” EIA Independent& Analysis Statistics U.S. Energy Information [online]. Available: https://www.eia.gov/totalenergy/data/browser/ [Accessed March 2021].

9. United Nations Climate Change,“The Paris Agreement,” UNFCC sites and platforms. [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement [Accessed March 2021].U.S. Energy Information Administration, “International Energy Outlook 2019. ” Delivered energy consumption by end-use sector and fuel. Region: Total world. EIA Independent& Analysis Statistics U.S. Energy Information [online]. Available: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=15-IEO2019&region=4-0&cases=Reference&f=A [Accessed March 2021].

10. K. Lucas,“The Evolution of EIA’s Residential, Commercial, Industrial, and Transportation Forecasts,” March 2016. [Online]. Available: https://www.ase.org/blog/evolution-eias-residential-commercial-industrial-and-transportation-forecasts

11. United States Environmental Protection Agency,"Energy and the Environment," Electricity Customers EPA United States Environmental Protection Agency. [Online]. Available: https://www.ase.org/blog/evolution-eias-residential-commercial-industrial-and-transportation-forecasts. [Accessed March 2021].

12. World Green Building Council,"New report: the building and construction sector can reach net zero carbon emissions by 2050," World Green Building Council [online]. Available: https://www.worldgbc.org/news-media/WorldGBC-embodied-carbon-report-published

13. Hong, Tianzhen, Feng, Wei, Lu, Alison, Xia, Jianjun, Yang, Le; Shen, Qi; Im, Piljae, Bhandari, and Mahabir,"Building Energy Monitoring and Analysis," Lawrence Berkley National Lab, California, USA, LBNL-6597E, June 2013 https://www.osti.gov/biblio/1129525

14. E. Doris, J. Cochran, and M. Vorum,"Energy Efficiency Policy in the United States: Overview of Trends at Different Levels of Government," National Renewable Energy Lab, Colarado, USA, Tech. Report NREL/TP-6A2-46532, Dec. 2009

15. G. Luicani, (2020), Lecture-7: Security of Supply and Demand [MOOC Lecture]. Politics and Economics of International Energy, ScincesPo [Online Course] https://www.coursera.org/learn/global-energy#about

16. E. Doris, J. Cochran, and M. Vorum,"Energy Efficiency Policy in the United States: Overview of Trends at Different Levels of Government," Chapter 1 Introduction, National Renewable Energy Lab, Colarado, USA, Tech. Report NREL/TP-6A2-46532, Dec. 2009

17. Office of Energy Efficiency and Renewable Energy,"Energy Codes 101: What Are They and What is DOE's Role?," Office of Energy Efficiency and Renewable Energy, An Office of Department of Energy [online]. Available: https://www.energy.gov/eere/buildings/articles/energy-codes-101-what-are-they-and-what-doe-s-role [Accessed March 2021].

18. Office of Energy Efficiency and Renewable Energy,"Why Building Energy Codes?," Office of Energy Efficiency and Renewable Energy, An Office of Department of Energy [online]. Available: https://www.energycodes.gov/about/why-building-energy-codes [Accessed March 2021].

19. Office of Energy Efficiency and Renewable Energy,"State Building Energy Efficiency Codes," Office of Energy Efficiency and Renewable Energy, An Office of Department of Energy [online]. Available: https://www.energycodes.gov/about/statutory-requirements [Accessed March 2021].

20. Office of Energy Efficiency and Renewable Energy,"Building Energy Codes Program (BECP) Activities Framework," Office of Energy Efficiency and Renewable Energy, An Office of Department of Energy [online]. Available: https://www.energycodes.gov/sites/default/files/documents/BECP%20Activities%20Framework.pdf [Accessed March 2021].

21. Federal Energy Management Program,"About the Federal Energy Management Program," Office of Energy Efficiency and Renewable Energy [online]. Available:

https://www.energy.gov/eere/femp/about-federal-energy-management-program [Accessed March 2021].

22. S. Koeppel and D. Ürge-Vorsatz,"Assessment of Policy Instruments for Reducing Greenhouse Gas Emissions from Buildings," December 2006. [Online] Available: https://www.researchgate.net/publication/264083534_Assessment_of_Policy_Instruments_for_Reducing_Greenhouse_Gas_Emissions_from_Buildings [Accessed March 2021].

23. Z. Afroz, G. Higgins, T. Urmee, and G. M. Shafiullah,"Technological Advancement of Energy Management Facility of Institutional Buildings: A Case Study," Energy Procedia, Volume 142 Pages 3088-3095, December 2017 [Online serial]. Available: https://www.sciencedirect.com/science/article/pii/S1876610217362045#cebibsec1 [Accessed January 2021].

24. G. Trencher, V. Castán Broto, T. Takagi, Z. Sprigings, Y. Nishida, and M. Yarime,"Innovative policy practices to advance building energy efficiency and retrofitting: Approaches, impacts and challenges in ten C40 cities," Environmental Science & Policy, vol. 66, pp. 353-365, 12// 2016.

25. M. Mardookhy, R. Sawhney, S. Ji , X. Zhu, W. Zhou ,"A study of energy efficiency in residential buildings in Knoxville, Tennessee," Journal of Cleaner Production, 85 (2014), pp.241-249.

26. M. R. Brambley, D. Hansen, P. Haves, D. Holmberg, S. McDonald, K. Roth, et al.,"Advanced sensors and controls for building applications: Market assessment and potential R&D pathways," Pacific Northwest National Laboratory, 2005.

27. Z. Ma, P. Cooper, D. Daly, L. Ledo,"Existing building retrofits: Methodology and state-of-the-art," Energy and Buildings, 55 (2012/12/01/ 2012), pp. 889-902. [Online serial]. Available: https://www.sciencedirect.com/science/article/pii/S1876610217362045 [Accessed January 2021].

28. DTE Energy,"Building Operation and Maintenance Initiatives (BOMI)," Introduction to Energy Management, Created for E-Challenge 2020, January 2020, [online]. Available: https://umich.app.box.com/file/641833095921

29. T. Hong, W. Feng, A. Lu, J. Xia, Yang, L., Shen, Q., Im, P., M. Bhandari,"Building energy monitoring and analysis," Lawrence Berkeley National Laboratory, June 2013. LBNL-6597E

30. "Energy Management Handbook," University of Michigan-Dearborn, Appendix-C Page-256, April 30 2020.

31. N. R. Tague,"The Quality Toolbox Second Edition," ISBN: 978-0-87389-639-9.

32. D. R. Kiran,"Seven Traditional Tools of TQM," Total Quality Management, Key Concepts and case studies [online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128110355000209

33. Land-of-Sky Regional Council (LOSRC),"A Strategic Energy Management Plan Model," Waste Reduction Partners, North Carolina, U.S.A. 2008, [online]. Available: https://files.nc.gov/ncdeq/Environmental%20Assistance%20and%20Customer%20Service/I

AS%20Energy%20Efficiency/Tools/strategic_energy_management_planning-k-12_and_community_college.pdf

34. President's Commission on Carbon Neutrality,"Final Report & Recommendations," University of Michgan, March 2021. [online]. Available: http://sustainability.umich.edu/media/files/U-M-Carbon-Neutrality-Final-Report-2021.pdf
35. Dr. T. W. M. Salih,"Insulation Materials for Undergraduate Students," Department of Engineering Materials, Al-Mustansiriyah University 2015. [online]. Available: https://uomustansiriyah.edu.iq/media/lectures/5/5_2016_05_01!08_28_51_PM.pdf
36. J. Straube,"High Performance Enclosures," Building Science, University of Waterloo [online]. Available: https://buildingscienceeducation.net/wp-content/uploads/2016/02/Control-Layer-definitions-glossary.pdf [Accessed November 2020]
37. EnergyPlus Software, Basic File, Office of Energy Efficiency and Renewable Energy, [online] Available: https://energyplus.net/
38. S. Schiavoni, F. D'Alessandro, F. Bianchi, and F. Asdrubali,"Insulation materials for the building sector: A review and comparative analysis," Renewable and Sustainable Energy Reviews 62, 2 May 2016,
39. Structural Engineering Institute, " What is Embodied Carbon? " [online]. Available: https://se2050.org/resources-overview/embodied-carbon/what-is-embodied-carbon/ [Accessed March 2020]
40. European Committee for Standardization, EN 13501-1:2007A1 2010. Fire classification of construction products and building elements—Part 1: Classification using data from reaction to fire tests.
41. F. Asdrubali,"The role of Life Cycle Assessment (LCA) in the design of sustainable buildings: Thermal and sound insulating materials," In: Proceedings of Euronoise 2009. Edinburg, Scotland.
42. F. Asdrubali,"Survey on the acoustical properties of new sustainable materials for noise control," In: Proceedings of Euronoise 2006. Tampere, Finland.
43. EnergyPlus Software, Inbuilt Material Data, Office of Energy Efficiency and Renewable Energy, [online] Available: https://energyplus.net/
44. S. Schiavoni, F. D'Alessandro F. Bianchi, and F. Asdrubali,"Insulation materials for the building sector: A review and comparative analysis," Table 6, Page 994, Renewable and Sustainable Energy Reviews 62, 2 May 2016.
45. Technical datasheet available at: http://www.matweb.com/errorUser.aspx?msgid=2&ckck=nocheck
46. S. Schiavoni, F. D'Alessandro F. Bianchi, and F. Asdrubali,"Insulation materials for the building sector: A review and comparative analysis," Table 5-6, Page 992&994, Renewable and Sustainable Energy Reviews 62, 2 May 2016.

47. U.S. Department of Energy,“Guide to Home Insulation,” DOE/EE-0340, ” [online]. Available: https://www.energy.gov/sites/prod/files/guide_to_home_insulation.pdf?o=600605&l=dir&qsrc=990&qo=contentPageRelatedSearch&ad=dirN [Accessed March 2020].

48. Dr. S. Pisupati, Professor, Department of Energy and Mineral Engineering,“EGEE 102, Energy Conservation for Environmental Protection,” College of Earth and Mineral Sciences, The Pennsylvania State University. [online]. Available: https://www.e-education.psu.edu/egee102/node/2070#:~:text=Heat%20loss%20from%20the%20walls%3A,wall%20needs%20to%20be%20calculated.&text=Total%20heat%20loss%20from%20the,116.99%20million%20BTUs%20per%20year [Accessed March 2021].

49. National Oceanic and Atmospheric Administration, NWS Forecast Office, Chicago, Illinois, National Weather Service, [online]. Available: https://www.weather.gov/lot/ord_rfd_monthly_yearly_normals,%20and, [Accessed January 2021].

50. S. Schiavoni, F. D'Alessandro F. Bianchi, and F. Asdrubali,“Insulation materials for the building sector: A review and comparative analysis,” Survey on commercialized insulation materials, Page 992-997, Renewable and Sustainable Energy Reviews 62, 2 May 2016

51. First Year Course module,“Decision making process,” UMass, Dartmouth U.S.A. [online]. Available: https://www.umassd.edu/fycm/decision-making/process/ [Accessed February 2021].

52. R. V. Vargas,“Using the analytic hierarchy process (ahp) to select and prioritize projects in a portfolio,” Paper presented at PMI® Global Congress 2010—North America, Washington, DC. Newtown Square, PA: Project Management Institute.

53. F. A. Paker, C. Alppay, and B. Sertyeşilişik,“Use of the AHP Methodology in Vehicle Design Process Dynamics: Determination of the Most Effective Concept Phases for the New Automotive Product,” Figure 6, December 2017 Journal of Transportation Technologies.

54. B. A. Morris,“Strength, Stiffness, and Abuse Resistance,” Chapter 9, The Science and Technology of Flexible Packaging, 2017, [online]. Available https://www.sciencedirect.com/science/article/pii/B9780323242738000095?via%3Dihub

55. Maps of World,“World Map showing list of top ten countries by Coconut production in the world,” [online]. Available https://www.mapsofworld.com/world-top-ten/world-map-coconut-production-countries.html [Accessed March 2021].

56. Kevin,“Coconut Coir: What It Is, How To Use It, And The Best Brands To Buy,” Epic Gardening, September 2018 [online]. Available https://www.epicgardening.com/coconut-coir/ [Accessed March 2021]

57. M.J. Dinesh,“Coconut Fiber Types & Process of making coconut Fibre,” Published: January 30, 2016, [online]. Available https://dinmj.medium.com/coconut-fiber-types-process-of-making-coconut-fibre-10455f0e2c8 [Accessed March 2021]

58. Andrea,“Coco Coir: What is it? When to use it? Better than peat?,” Your Indoor Herbs, [online]. Available https://yourindoorherbs.com/coco-coir-what-is-it-when-to-use-vs-peat/ [Accessed March 2021].

59. ITCOT Consultancy and Services Ltd, Detailed Project Report Cluster Location: Tirunelveli, Tamil Nadu (Tenkaasi Podhigai Coir Consortium (P) Ltd.,),” Coir Board, Kochi, India, Available http://coirboard.gov.in/wp-content/uploads/2016/03/Final-DPR-Tirunelveli-Tenkasi-Writeup1.pdf [Accessed March 2021]

60. Online software, Environmental Protection Agency,“Greenhouse Gas Equivalencies Calculator,” United States Environmental Protection Agency, An official website of the United States government. [online]. Available https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator [Accessed March 2021].